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A COMPENSATION FOR VISUAL LOSS

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13. ABSTRACT (Maximum 200 words) Loss of the central visual field, or foveal scotoma, due to accidental exposure to laser light or macular disease can cause serious impairments in visually guided performance. Either long lasting afterimages from visible radiation or permanent degenerative injury to retinal cells may interfere with high resolution image acquisition for target recognition and normal control of eye fixations and saccades. Development of an electronic aid is described using a scotoma simulator method to safely duplicate and experimentally control foveal scotoma size, shape, and position in normal subjects. The electronic aid is switched into the system by video mixing through a software controlled raster display. Images normally falling within the scotoma boundary are shifted in real time to the highest resolution spared retina. The aid unblocks visual images inside a scotoma and also reduces abnormal eye movements which accompany adaptation to visual loss.				
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FOREWORD

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Aided Recovery From Visual Loss

INTRODUCTION

Loss of foveal vision from disease or accidental exposure to bright light seriously impairs visual functions like reading and visual search. A range of studies on low vision patients with scotomas from macular disease and simulated scotomas in normal observers, as well as animal studies of adaptation to loss of the central visual field functions, have demonstrated the value and limitations to unaided eccentric or off axis viewing as a compensation for loss of foveal vision. In military contexts, the widening use of lasers for sighting, range finding, and communications poses a threat to human vision in the form of scotomas from retinal exposure aftereffects. The visual impairments of laser induced foveal scotomas, which block foveal visual acuity and may impair functioning as much as an advanced disease process, have been identified as a significant and evolving problem (O'Mara, Stamper, Lund, and Beatrice, 1980; Stuck, 1982; Menendez and Smith, 1990; Green, Cartledge, Cheney, and Menendez, 1991) during military operations and training.

The work described in this proposal tested a concept simulator for image shifting, as a countermeasure for central scotomas. Central scotomas produce large losses in visually guided performance because central vision has the best visual resolution compared to more peripheral retina (Ludvig, 1941), and central retina is also important in the normal reflexive pattern of eye movement which brings targets detected in the periphery to the central retina for recognition. In image shifting, the portion of the central visual field corresponding to the scotoma is copied into a computer memory and is rapidly re-displayed on the highest resolution peripheral retina outside of the scotoma area (see Figure 1). The image shift method automates the naturally occurring adaptation to loss of central vision, called eccentric viewing, which some macular disease patients employ to position targets of interest on spared seeing retina.

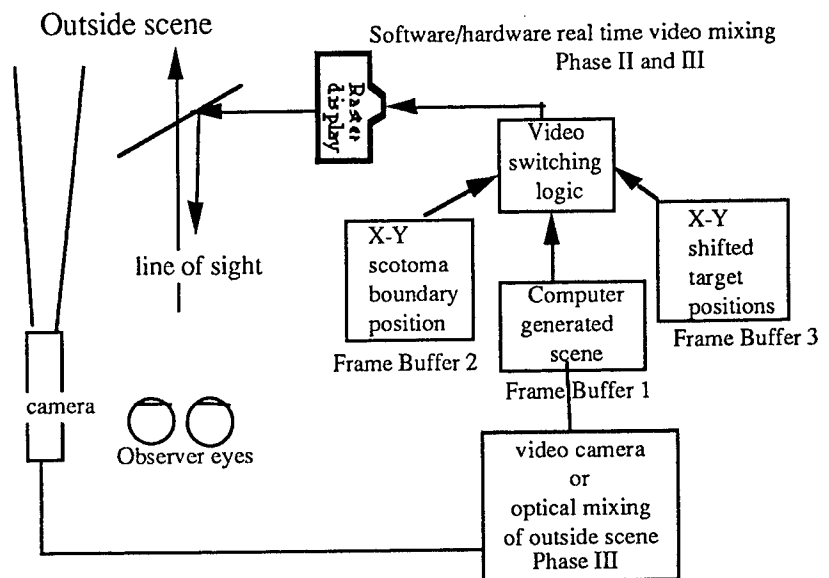
The automated image shift method addresses two important impairments resulting from a central field scotoma. First, the scotoma blocks information usually accessible to fovea so that a target is completely missed when it is hidden inside the scotoma area. Second, central scotomas produce slow drift, and reflex foveations that place the target within the boundary of the non seeing scotomatous retina. The drift is associated with a "scotoma nystagmus" that pushes targets even farther into the lower resolution periphery. Reflex foveations with the scotoma are difficult to eliminate even after extensive practice at eccentric viewing (Bertera, 1991) probably because of the over learned sequence of directing attention to periphery followed by foveal fixation.

There are several advantages to an automated image shifting method over unaided eccentric viewing to compensate for central visual loss. First, there is consistency in maintaining an eccentric view of the target as well as accuracy in positioning the target image on the highest resolution remaining retina. The importance of consistency and

accuracy is demonstrated later in studies showing that unaided scotoma adaptation is incomplete even after significant practice supported with feedback about eye position. Electronic image shifting may also reduce or eliminate abnormal eye drift and reflex foveations with their associated corrective saccades, common in unaided eccentric viewing.

Image shifting uses the normal pattern of peripheral attention to foveal fixation as a designator to direct the electronic image shift system. Instead of trying to break up or inhibit the normal reflexive pattern of eye movement that brings peripheral targets to fovea, the image shift method employs the reflex to designate the targets of interest. After an area of interest has been designated a computerized graphic controller can then rapidly re-display the area in a position outside of the scotoma.

Figure 1. The Image Shift system will be implemented with a set of video memory buffers that combine the visual scene view (computer generated images or outside scene from camera) with the scotoma (blanked) portion of the scene and the shifted images of targets that are inside the scotoma boundary. To test the parameters of system operation (scotoma size, target size & delay of image shifting) a simulated scotoma under experimental control is fed into the video logic from a separate buffer in Phase II. In Phase III, the straight through outside optical scene is mixed with a raster display of the shifted and/or enhanced targets, designated by the system as inside the scotoma boundary.



Area of interest displays, controlled by eye movements, have been used in the past in experimental flight simulators to enhance images in the central field to match the resolution of the central retina. However, an essential difference in the present proposal is the rapid translation of a portion of the visual field image away from fovea, not simply a change in the pixel density or contrast. This means that an image area may appear to jump from one portion of the display to another at each eye movement when the eye movement and image movement are closely linked in time. While such a close linkage of eye movement and image jumps might be useful in rapidly re-displaying the scotoma area image to a seeing area of peripheral retina, repeated image jumps could stimulate the visual motor and information processing systems with many temporal transients. Therefore, an important objective in this research and development effort was to determine the parameters for image shifting for providing consistent, accurate and rapid shifting from scotoma to seeing retina, without triggering unwanted reflexive movements during the repeated process of shifting that might reduce the efficiency of image shifting.

This project will further develop an image shifting system to a first prototype stage that will be tested with visual signals required in operational military contexts, as well as reading and object recognition tasks useful to low vision readers. A useful and feasible system should improve visually guided performance relative to other available methods for scotoma compensation to a sufficient degree to justify the cost.

RATIONAL AND SYSTEM ELEMENTS

Eye Movements and scotoma fixations

The image shifting system will be directed by the observers own eye movements, detected as a position of gaze in the visual display. Normally, the observer sees a target of interest in the peripheral visual field and then makes an eye movement to bring that target to central retina, the fovea. Foveal vision is distributed around the visual display in pauses called eye fixations at about three per second during visual search (Ford, White and Lichtenstein, 1959) and reading (e.g., Rayner and Bertera, 1979). Each fixation is followed by a flicking eye movement called a saccade, or saccadic eye movement, which delivers a new visual field location to fovea. Smooth, lower velocity eye movements are used to pursue moving targets or to compensate for head movement. After a target of interest has been detected in peripheral vision, both slow and saccadic movements may serve to stabilize the target on fovea.

The accuracy of the normal foveating saccades made in response to seeing a peripheral target is generally quite good which makes it possible to use these foveations as a signal or designator to direct the image shifting system. While accuracy falls as saccade size increases, normal subjects can bring a target to within 10 or 20 minarc of their fovea in a single movement, from peripheral locations as far as 10 degrees away. This means that a target can be detected outside of even a very large scotoma (i.e., 20 degrees in diameter) and its location can be used to program an accurate saccadic eye movement. The saccade size is calculated within the oculomotor system as the distance from the peripheral target to fovea. The saccade is accomplished under most circumstances as a ballistic movement without feedback about accuracy while the eye is actually moving, until the eye slows down and stops in an eye fixation. During a normal fixation without a scotoma, which may last from approximately 100 msec to 450 msec, a secondary or corrective saccade can be generated if the target is not positioned closely enough to fovea. Of course, when a target image lands within an absolute central field scotoma there is no information about the accuracy of eye position and no guidance for a corrective saccade.

Such foveations with the scotoma, or encroachment of the scotoma boundary anywhere on the target, are called scotoma fixation errors, i.e., the scotoma area is used to fixate on the target. The proposed image shift system uses scotoma error fixations to designate or point to the target area of interest, so that it can be copied and shifted to seeing peripheral retina. Unaided eccentric viewing requires inhibition of the normal reflex to foveate a peripheral target of interest. The mechanism for inhibition of this normal foveation reflex is not known, but the errors detected in previous studies of eccentric viewing clearly indicate that inhibition of scotoma foveations is incomplete even after extensive practice. In unaided eccentric viewing, scotoma fixations may serve an indirect purpose of ranging the edge of the scotoma to maintain the offset for programming adapted saccades and for maintaining a steady eccentric viewing position outside of the scotoma boundary. Therefore, scotoma fixations may be a naturally occurring part of the oculomotor control system and although they serve to conceal targets for significant periods they could serve an important purpose in unaided eccentric viewing.

The optimum unaided scotoma adaptation is to translate the landing position of the eye for each movement by making peripheral to peripheral saccades, instead of the normal fovea to fovea saccades, while maintaining a normal saccade length or saccade gain. However, after scotoma fixation errors, subjects must make a significant portion of their saccades longer or shorter than normal to move the scotoma boundary either beyond or before the target, i.e., an increase or decrease in the gain of the saccadic system (McLaughlin, 1967; Miller, Anstis & Templeton, 1981). Mixtures of translation and gain

change strategies may complicate unaided adaptation because the two methods are mutually incompatible. Further, undershooting and overshooting required for a gain change are not learned at the same rate; gain changes learned with a specific target do not transfer automatically to other targets; and the gain for one target may be increased while the gain for another may be decreased (Miller et al. 1981).

A further problem in making a series of unaided saccades with a scotoma is the disappearance of the target with foveal fixation. Repeated attempts at foveal fixation with a scotoma amount to practice with a disappearing image on landing, that eliminates the object of fixation. Using repeated scotoma fixations as a designator for an image shift system requires consideration of changes in the oculomotor control during practice or use. In automated image shifting the subject must refrain from making corrective movements to position a target on eccentric retina. The image shift system does this by itself and a duplication of this function by the subject would produce disordered eye movements as the eye "chased" the repeated corrective movements of the shifted image. If target disappearance on foveal landing produces an adaptation response such as a change in saccade gain without any voluntary effort, it should be noted in the present studies since this might compromise the accuracy of the scotoma fixation as an image shift system designator.

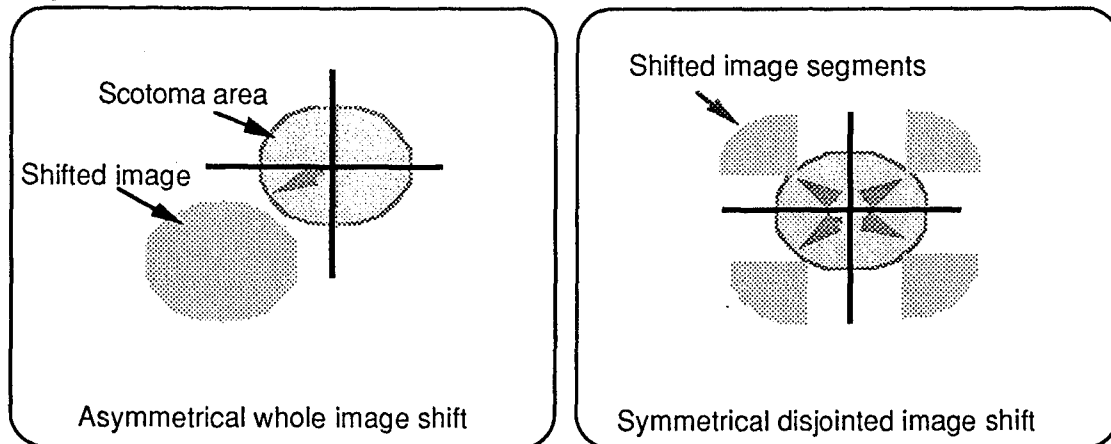


Figure 2. Two image shift strategies for transplanting an image from a scotoma area centered on the fovea (crosshairs) to spared peripheral retina. Disjointing the shifted image while retaining a symmetrical displacement may fragment spatial attention. Magnification of any shifted image would be required to maintain same resolution (number of receptors) from fovea to periphery. Many other shift strategies are possible but more complex image processing may produce perceptual problems such as perceived movement of targets as image shifting is repeated at different display positions.

Selection of the transplant area

The general strategy for shifting an image out of the scotoma area is to use a single peripheral transplant site as a "neo-fovea." An alternative strategy could employ a variety of image divisions such as a symmetrical quadrant dislocation, pushing the image segments outwards around the edges of the scotoma (Figure 2). An asymmetrical whole image shift was chosen for the image shift strategy for the present proposal to minimize the image processing problems and the distribution of attention at four locations required in a dislocated image.

While plasticity is available for adaptation of peripheral viewing positions subjects apparently have strong preferences for selecting one location over another. The reasons for

preferences are not known, but arbitrarily selected viewing position preferences could be used for consistency or habit formation, or for compatibility with some neural wiring. The design of the image shift system will take these preferences into account in selecting a transplant area.

The selection of the transplant area is dependent first on the size of the scotoma. The size of a scotoma can vary from single laser burn sizes of 50 microns (Beatrice, 1982) upwards. For larger foveal centered scotomas (e.g., >2.0 degrees), visual search, reading text or instruments, or detail vision becomes difficult or impossible. Disease related scotomas can vary widely in size but macular holes and retinal detachment can produce well defined, measurable scotomas from 0.5 degrees to 5 degrees in diameter. The area of an absolute scotoma is defined as completely unresponsive to light. In the same sized relative scotoma there may be uneven gradations of contrast reduction, color changes, or metamorphopsia, i.e., a geometric change in visual image due to retinal membrane distortion. In traumatic injuries due to exposure to laser energy the scotoma size may be affected by the presence of pulsed sources where there is a likelihood that multiple burns or afterimages might be produced in a single incident, linked by some function of eye rotation, inter-pulse interval, and pulse duration. Further, multiple scotoma geometry may create a coalescing effect or a "fill in" of the dysfunctional area, perhaps similar to the perceptual filling of a blind spot (Kawabata, 1983), resulting in larger deficits than predicted by a simple additive model for laser spot sizes.

An important variable in selection of the transplant image area is the relationship between the size of the scotoma image and the size of the anticipated targets. Scotomas smaller than a target image would require mutilation of the target image in an image transplant operation if only the scotoma area were copied and shifted to peripheral retina. This image mutilation process is shown in Figure 3 for two different target images and it is clear that for some target images and scotoma sizes an image shift area that matches the scotoma size will make the shifted image less recognizable. A partial remedy for such image truncation may be found in an image shift system which transplants as large an image as feasible to the periphery no matter what the scotoma size. This makes the process more predictable for the subjects. A standard transplant area also eliminates the need of specifying the size of the scotoma as a system requirement before use. This is reasonable since some form of visual field mapping of the size of a scotoma would be too time consuming to implement with an immediate threat from loss of vision. An alternative is to make the transplant area easily adjustable so that it can be tailored or individualized for each scotoma size and type, and perhaps for the visual image configuration that might be present in a specific context. Adjustment in the transplant area size and scotoma size will be included in the experimental tests of a proposed Phase II automated image shift system.

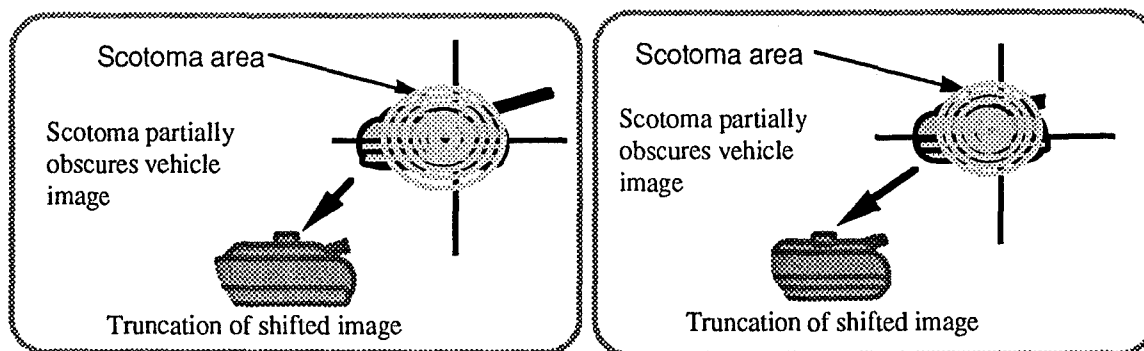


Figure 2. Image shifting with small scotomas can create fragmented shifted copy when target image is larger than scotoma, making recognition of friend or foe difficult, demonstrated in this tank barrel length, different targets made equivalent by fragmented image shift. Image distortion and truncation could be limited by using a copy and shift window larger than anticipated target images and larger than anticipated scotomas.

The scotoma size variable could also be complicated by differences in the depth of the scotoma or the degree of relative light insensitivity across its area. Choosing an image shift area based only on the size of the absolute scotoma area may underestimate the area of visual dysfunction. A relative scotoma may be just as impairing to some recognition performance as an absolute scotoma. The Phase II studies will include tests of relative scotomas using contrast reductions across the scotoma area, i.e., a central area of absolute scotoma and an outer annulus of relative scotoma, were proposed to broaden the scotoma characteristics used to test of the shifting system and therefore broaden the generality of the results.

The subjective appearance of a scotoma from chronic retinal disease or abrupt retinal detachment incidents may be quite different from a scotoma due to exposure to laser radiation or other bright light sources. For example, it is well known that the initial effect of a laser burn on retina may be an afterimage (from visible light) along with an absolute scotoma in the exposed area. Afterimage scotomas may appear as a bright spot in central vision if viewed on a dark background (Brindley, 1962; Trezona, 1959), but visibility may depend on the relative contrast of the visual field. The apparent afterimage polarity can be reversed by a brighter background, i.e. the scotoma may appear as a darker area on a light field, or the afterimage scotoma can appear as a lighter area in the presence of a dark visual field. It should be noted that low visibility for the scotoma, or a low or zero performance decrement due to loss of central vision may temporarily conceal the presence of a scotoma, reducing the adaptation response. Further, post light exposure edema may produce secondary tissue damage, expanding the scotoma size, perhaps with an annular ring of relative scotoma around an absolute central scotoma, so that an histological abnormality of 100 μm on the retina may underestimate the true area of dysfunction. Using the visible afterimage area to match a size for the scotoma and image shift system is a possibility but assumes that the scotoma and the afterimage are the same size.

Synchronizing image shift with saccades

In an image shift system with sufficient throughput, repeating sequences of image movements and eye movements could be generated by "chasing" the eye controlled image. A feedback loop of eye movement and image movement would be created by the transient

visual signal produced by the peripheral onset of the sifted image. The transplant onset could trigger a foveation reflex and yet another image shift, running on into an open loop condition that would slew the images and eye across the visual field as a pursuit eye movement. The transplant offset, or the replacement of the target to its true location could also create a transient peripheral signal that might stimulate pursuit eye movements. Asking subjects to inhibit these pursuit reflexes could be as difficult a task to perform reliably as the inhibition required in unaided eccentric viewing, and, this would argue against the feasibility of the image shift method.

One simple way to address the issue of stimulating unwanted saccades with the onset of the shifted image is to delay the onset of the peripheral shifted image to avoid the throughput required for an open loop condition. Increases in the interval between a current fixation point and a target onset lengthens the saccadic reaction time (Boch and Fischer, 1983). In the image shift paradigm the objective is to prevent most of these saccades altogether, and therefore, beginning the image shift system development with parameters that create the longest saccade reaction time is a good starting point. The "worst" case for our purposes, i.e., stimulus onsets that produced the fastest reactions were when the target stimulus occurred simultaneously with the offset of a central fixation spot.

Another method of reducing open loop errors is to lower the spatial and temporal bandwidth for image shifting by transplanting an image only when an eye fixation criteria is satisfied rather than for individual samples of eye position. For example, an eye fixation criteria can be defined as eye position sample sets which remain within 10 minarc for at least 90 msec. For small saccades or short drift movements, an image shift delay would keep the shift image stable and reduce open loop effects. A secondary advantage to using an eye fixation criteria with delays is that fewer shifts would conserve spatial attention, which presumably would be required to change a great deal if an image was moved frequently with each eye position sample change.

The exact relationship between programming attentional shifts and eye movements is not clear (Krose and Julesz, 1989), however, it is generally agreed that movement of attention to a peripheral target of interest precedes an eye movement (Posner, 1980). The entire process is accomplished first by disengaging attention and fixation (motor) control from the current target (e.g., Fisher, 1987) and re-engaging both attention and fixation control, along with the actual movement of both attention and the eye (Nakayama, 1993). Further, it is generally conceded that shifts of spatial attention are carried out roughly on the order of speed of actual eye movements. If such a variety of processes are stimulated with every image shift movement then it seems reasonable to adopt an image shift criteria which produces as few shifts as necessary for compensation for the scotoma.

Scotoma size and task difficulty

In an earlier study of simulated scotomas, sized to approximate laser spot sizes, task demands were shown to modify scotoma deficits in several multiple target search tasks. Relatively small central field scotomas can produce large impairments in visual search if tasks require a high degree of foveal vision (Bertera, 1988). Simulated loss of 20 minarc of the central visual field was associated with a doubling in the search time and under some conditions significant (15%) increases in eye fixation duration (See Figure 4). In general, the impairment due to the scotoma became statistically stronger for search time as visibility was reduced. It appears that task conditions which require more foveal vision, such as seeing fine detail or discriminating similar contours or letters, are more sensitive to the impairing effects of a foveal scotoma. If foveal vision is not critical to a task, a foveal scotoma has very little effect, e.g. in visual search for targets with relatively large gaps, high contrast and with small scotomas (Bertera, 1988). Visual search targets which are smaller or lower contrast increase the deficit with a simulated scotoma (Figure 4).

Asymmetry in preferred viewing position

It has been determined that during scotoma adaptation subjects sometimes position their eyes in ways which are either asymmetrical, not optimum, or seem to generate abnormal eye movements even after extensive practice. It is useful to point out that there are preferences in viewing position in patient populations with clinical scotomas, in which eccentric viewing adaptation has had years to develop, before presenting asymmetries in eccentric viewing due to abrupt onset scotomas similar to accidental laser exposure. Cummings et al. (1985) found that 72% of patients with a central visual loss had developed a single, strongly preferred viewing position outside of the scotoma. Timberlake, et al. (1986) also determined that patients with long standing macular disease tend to use an area adjacent to the scotoma for eccentric viewing, called a preferred retinal

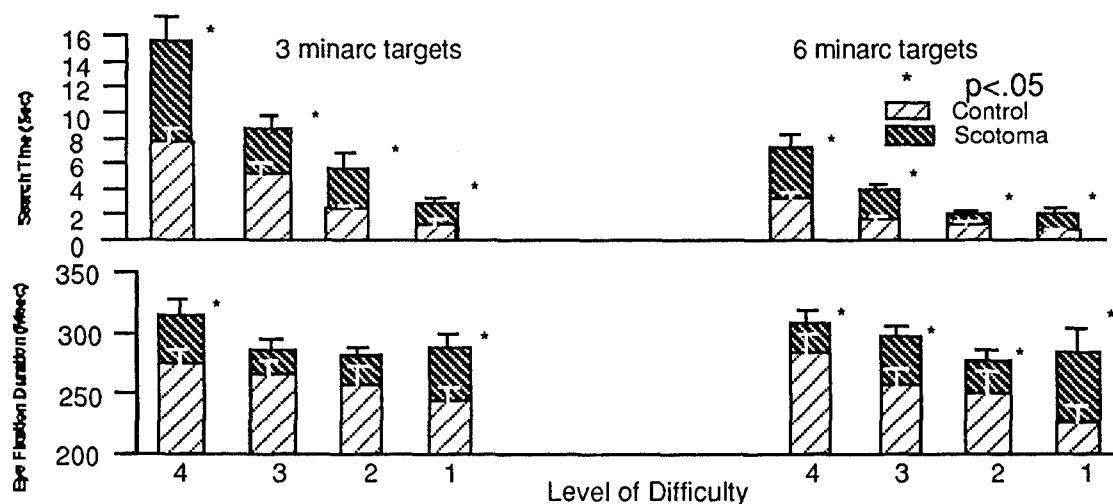


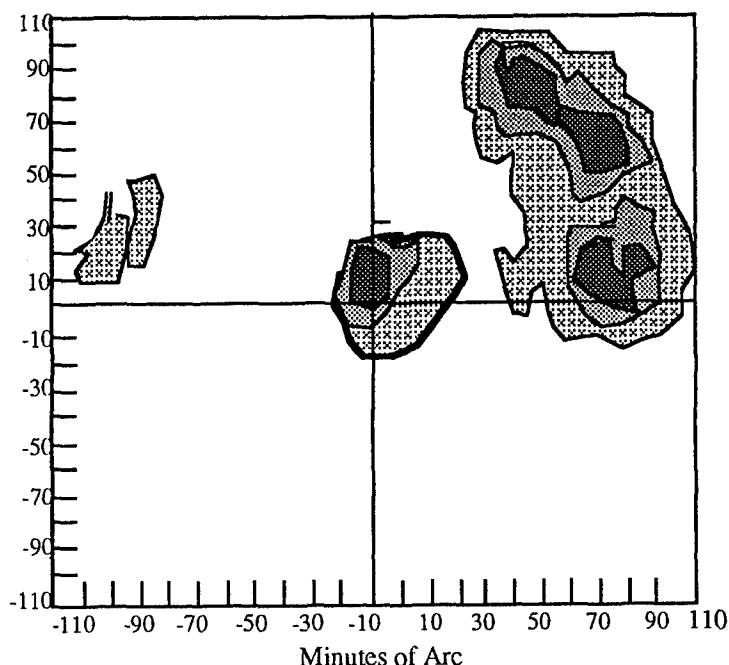
Figure 4. Search time and eye fixation duration for acuity targets with 3 or 6 minarc gaps. The level of difficult was a combination of search element density and relative contrast. The most difficult task (level 4) was to search for a small (3 minarc) gap of low contrast in a dense display (99 non-target elements). The large impairments in search and significant increases in eye fixation duration were found even though the simulated scotoma was only 20 minarc in diameter.

locus (PRL). However, their PRL was not necessarily as close as possible to the foveola, i.e., their strategy did not maximize resolution. White and Bedell, (1990) further determined that macular disease scotomas of 5, 10, or 20 degrees were associated with a preferred fixation area but re-referencing of eye movements to these areas was incomplete. Two earlier reports which measured eye movements with a scotoma, both with one subject, demonstrated some degree of eccentric viewing but without a clear preference for a defined eccentric viewing position (Zeevi, Peli and Stark, 1979; Whittaker and Cummings, 1986).

In a study of spontaneous adaptation to a simulated scotoma in six normal subjects, there was a marked preference to consistently position the scotomatous fovea out of the way to the upper right relative to the target (Bertera, 1992) even when subjects were free to look anywhere they choose (Figure 5). The subjects were required to hold the target in clear view with a 2.5 degree scotoma across their fovea which moved over background grid lines. This consistent, preferred fixation position translates into maintaining the target on the superior retina and as close to the scotoma border as possible, i.e. in the highest available resolution retina. It is probably no coincidence that clinical reports indicate that

patients are much more likely to notice deficits in vision when treatment or disease creates visual loss on the superior retina. This makes sense since the superior retina receives much more input from below the horizon field where there are more visual signals for daily activities.

Fig 5. Composite map of eye position samples for six subjects. The subjects attempted to keep a central target cross (located at intersection of lines) in clear as possible view for a total of about 300 sec with a 2.5 degree simulated scotoma across their fovea. Density of crosshatching indicates increasing % fixation positions. An asymmetry is obvious in the scatter of eye positions which were freely chosen by these naive subjects. All subjects claimed that the upper right fixation position "felt" easier than anywhere else. Clusters of eye positions near the center represent the most common error: fixating the target with the scotoma. Darker areas show greater total fixation time.



The upper right spontaneous asymmetry during steady eccentric viewing position has not been explained by simple asymmetries in eye control for different positions around a target. Bertera (1992) tested a series of alternative fixation positions around the target while subjects viewed with the scotoma to determine if some oculomotor instability could be detected at non-preferred positions. While the percentage of eccentric viewing was about the same for the alternative positions, non-significant asymmetries did emerge in longer fixation duration and better average eccentricity for the upper right position. There are many asymmetrical functions and cellular architectures across the retinal field (Estes and Wolford, 1971) that might be used to explain the left right asymmetry, such as, left-right biases from reading habits, cerebral hemisphere asymmetries for input and spatial attention, and the position of the optic nerve.

Scotoma nystagmus and drift

Another process to take into account in selecting an image transplant site is the production of abnormal eye movements generated by eccentric viewing processes. Subjects show general instability in eye control with an increase in saccades and a high proportion time spent in scotoma fixations, during the early phases of adaptation to a scotoma. After early adaptation, eccentric viewing develops and near normal stability may return for steady fixation tasks measured by an increase in fixation duration. It has been generally assumed that establishment of a stable eccentric viewing position, and increased fixation duration, is a sign of adaptation to a central scotoma. However, stable eccentric fixation and prolonged eye fixation durations may set the stage for the onset of drift or the slow phase of scotoma nystagmus.

These slow movements during eccentric viewing range from drift movements, some lasting 15 seconds, to repeated nystagmus-like movements consisting of drift with a saccadic return, called scotoma nystagmus (see Figure 6). Unlike other forms of nystagmus (optokinetic or vestibular) this scotoma "nystagmus" can be interrupted with verbal instructions to make saccades. The significance of such movements is that they redefine the eccentric viewing position as a track. The drift or scotoma track moves the average viewing position towards more peripheral or hyper-eccentric retina with poorer acuity. A drift or nystagmus track of 60 minarc would position the eccentric viewing point as much as twice as far away from the target as necessary, for example, with a 120 minarc radius scotoma.

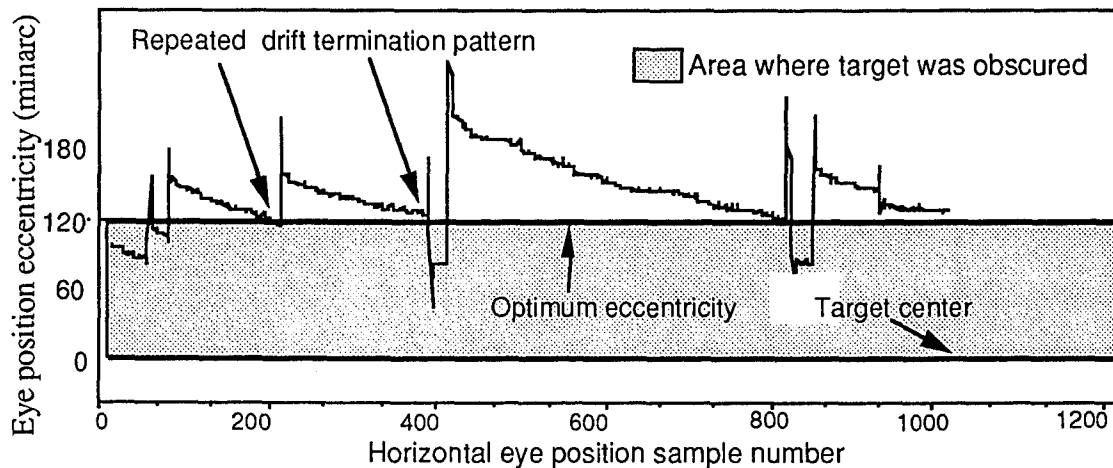


Figure 6. Eccentricity from target (minarc) is plotted for one record over samples (time). At 120 minarc, the optimum eccentricity, the target is visible. Repeated termination of drift as the scotoma boundary approaches the target generates a jerk nystagmus pattern. To avoid covering the target the subject must estimate the distance from fovea to target or from scotoma edge to target. The subject learns the extent of the scotoma boundary when target disappears inside it.

Steinman and Cunitz (1968) detected such drift eye movement while two subjects used eccentric viewing with a physiological scotoma and implicated them in the fluctuating visibility of targets, first noticed by Simon (1904). The scotoma was 20-40 minarc radius and corresponded to the subjects' low light physiological scotoma (a rod free area in foveal region that forms a "blind" hole in dim light). The two subjects both made drift movements toward the target location followed by return saccades. One subject preferred an eccentric viewing position in the upper right while the other preferred the upper left.

Steinman and Cunitz (1968) suggested that the drift was directed to a target disappearance point and that drift is guided by some retinal architecture or normal motor habit for fixation control. Whittaker, Budd and Cummings (1988) found drift eye movements with scotomas in three more subjects and showed that drift slow phase can be consistently towards other directions than the target, i.e., the normal fixation locus. Whether drift was target directed or not was idiosyncratic.

Bertera (1990) and Bertera (1991) measured eye movements during the early scotoma adaptation period and found repeated drift movements with normal subjects with simulated scotomas. Five subjects emitted drift eye movements with saccadic returns, but only after the initial period of adaptation when error saccades were minimized and the eccentric viewing position "settled down" to a stable vantage point. All the subjects showed periods exclusively of drift which brought the scotoma edge near an optimum position to the target followed by saccade returns, similar to jerk nystagmus.

The drift directions were consistent and idiosyncratic under increasing scotoma sizes. One subject consistently drifted away from the target, the rest of the subjects showed drift vectors either in centripetal (target directed) or oblique directions. The target directed drift movements were strategic since they often ended before the scotoma actually obscured the target (Figure 6). This subject shows a typical drift amplitude of about one degree. The drift velocity ranged from 20 to 120 minarc/s. The drift or slow phase wave form appeared mixed: sometimes with a decreasing velocity; more often with a constant velocity. Drift was a significant portion of the total viewing time, averaging 58%. Other drift patterns demonstrate a good deal of adaptability and strategy in eccentric viewing position. The subject in Figure 7 is typical: rather than make saccades most subjects will adopt a position between two targets, whether it produces good performance or not, and drift down with

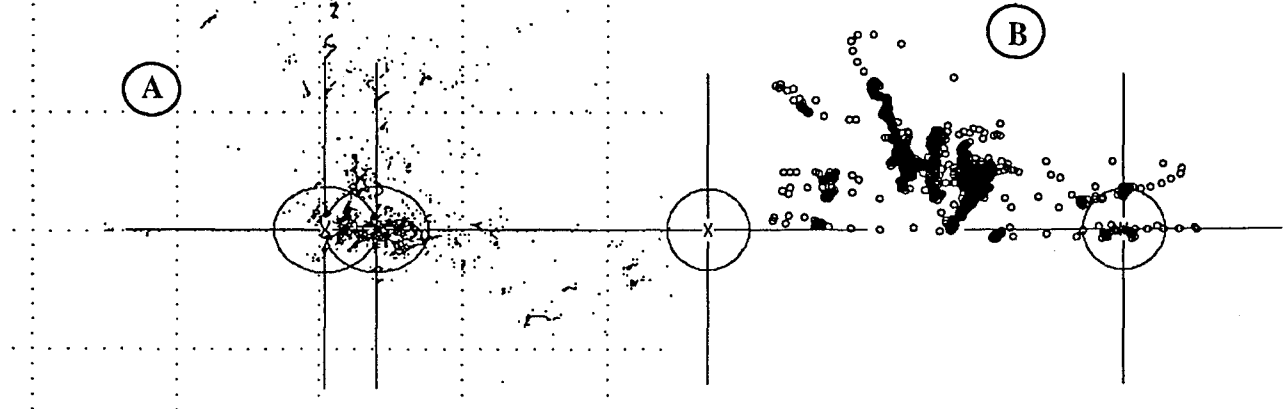


Figure 7. Horizontal and vertical eye position samples plotted relative to the two targets in the left-right saccade task (intersections of crosshairs), along with circular boundaries indicating where the target disappears inside the 30 minarc radius scotoma. Subject was instructed to look back and forth keeping target in view as much as possible. A majority of the eye positions placed the target inside of the scotoma (A), even after an hour of practice. Subjects tried to avoid making saccades whenever possible by selecting a strategic eccentric position in which both targets were visible (B).

upward return saccades. Besides unexplained asymmetry in the drift or nystagmus patterns between subjects, there appears to be asymmetry in the drift onset or amplitude within subjects when they use different eccentric viewing positions. Drift movements are much more degrading to acuity than simple low velocity smearing of the retinal image would imply, since at slow drift speeds a discrete target image spends as much as 25% percent of available viewing time on lower resolution retina due to hyper-eccentric return saccades at the end of each drift movement.

Hyper-eccentric viewing with steady fixation and saccades

After each drift movement there is a saccade to return the eye to a more favorable viewing position. Many of these compensatory saccades carry the eye past an optimum viewing position. The hyper-eccentric fixations and scotoma fixations account for a substantial loss in target viewing time (See Figure 8). The hyper-eccentric viewing associated with drift is also present in tasks which generate mainly saccades where more optimum positioning would place targets on higher resolution areas, presumably leading to better performance. Marked individual differences exist in the development of eccentric fixation among subjects and large excursions away from the target (hyper-eccentric fixations) are commonly represented in mean eccentricities for eye positions across subjects.

How does hyper-eccentricity relate to scotoma size? Hyper-eccentric adaptation to scotomas has the effect of enlarging the scotoma so that the spot size on the retina is an underestimate of the impairment. In a two target alternation task subjects must either adopt a strategy of peripheral to peripheral saccades or make corrective movements to a peripheral location after landing with the scotoma "covering" the target. An important implication of the degree of hyper-eccentricity is that an image shifting system may require design features to control accidental overlay when a shifted target is designated for transplant, by the rules of the shift algorithm, on top of a more distant target, outside of the scotoma.

Scotoma adaptation by unaided eccentric viewing begins rapidly, but large residual deficits in target visibility time and target resolution remain due to drift eye movements, scotoma foveations, and hyper-eccentric viewing. Electronic image shifting can address these problems. If the method is feasible both in effectiveness and bio-compatibility, so that large rapid improvements in visual performance are possible without triggering uncontrolled oculomotor reflexes, it may be a valuable compensation for foveal loss due to accident or disease.

Adaptation of saccades compared to steady fixation

Saccades and steady fixation must be discriminated during adaptation to a central field scotoma because these two patterns of eye movement and control are affected quite differently by a scotoma. If a subject tries to fixate a single stationary target in peripheral vision there are two processes which must be accounted for. Adjusting the eye position in small trial and error increments until the target is visible near the scotoma edge is required as the first step. Once an alignment of the target has been achieved the subject may need only to inhibit the reflexive tendency to fixate the target with the scotomatous fovea. However, if the target is moving, either smoothly or in jumps, the subject is not allowed to spend much time in the eccentric fixation position where inhibition of foveation is the main task.

When the target moves once per second the subject is required to make a series of saccades where each landing or fixation requires detection of the new target position, programming a saccade of the right length depending on the current eye position, and finally landing and checking to see if the target is outside of the scotoma boundary. Heinan and Skavenski (1992) addressed this problem in an animal model by ablating fovea bilaterally in monkeys. When required to maintain a steady eccentric view to a single stationary target, adaptation of fixation position was rapid and the animal was able to maintain the target outside of the scotoma boundary, much like the human subjects with a simulated scotoma (e.g., Bertera, 1990; Whittaker and Budd, 1988). However, in a second saccade tracking task, the target shifted around the display requiring repeated saccades to maintain the target in view outside of the scotoma. Here the subjects showed little adaptation and continued to make foveations with the scotoma area. It seems that fixation adapts but saccades do not. The reason probably lies in the processes of computing a landing position in the periphery and in defeating the reflex to land with fovea, which must be accomplished just before the saccade starts.

It might seem that the unpredictable character of target movement in a saccade tracking task could account for poor performance at programming an eccentric landing position for each saccade. When normal human subjects with a simulated scotoma perform a saccade production task in which the target positions are stationary, i.e., looking back and forth between a left and right target, saccade accuracy is still poor. The Image Shift aid is designed to take advantage of the stereotyped tendency to fixate the target with the

scotomatous fovea and by automatically shifting the target onto a peripheral retinal site outside of the scotoma, increase the target viewing time dramatically and reduce the number of error eye movements.

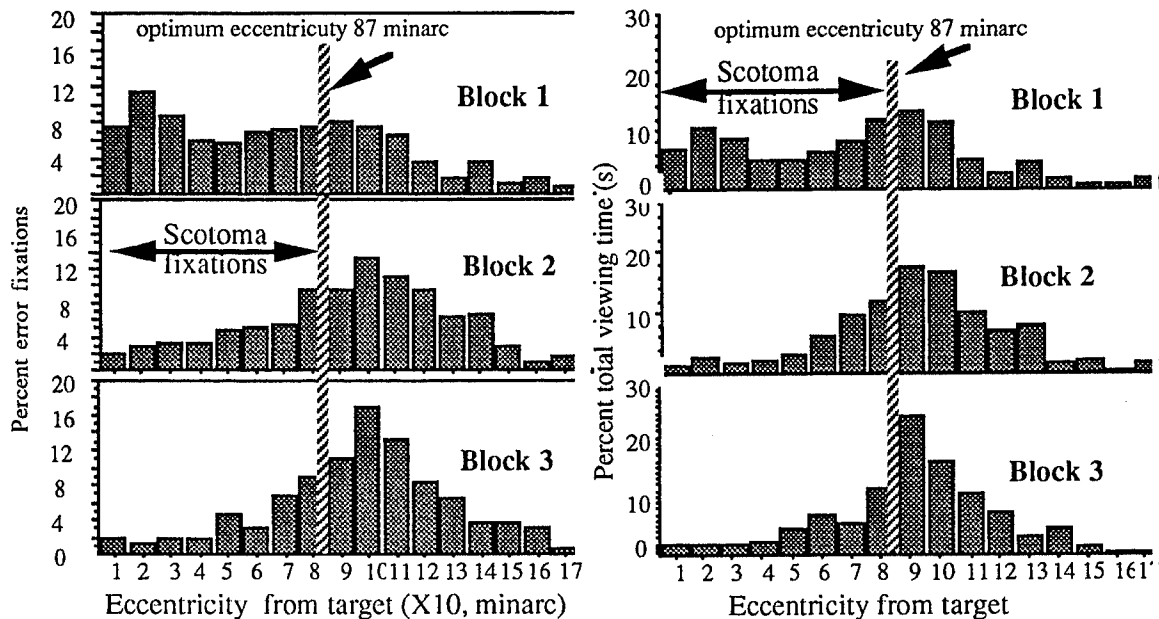


Figure 8. Development of eccentric viewing reduces % error fixations and % time spent with target hidden in scotoma area. Although optimum positioning of fovea at 87 minarc eccentric to the target was possible for brief periods, even after practice block 3 the target is still hidden about 25% the total possible viewing time. An additional 28% of time was taken with hyper-eccentric, lower resolution, fixation positions: target positioned farther in lower resolution periphery than necessary for scotoma-free viewing.

METHODS

System Components

The Phase I work identified three areas necessary to test an image shift system to compensate for central visual field losses due to accidental exposure to laser radiation or macular disease: hardware development, software development, and oculomotor and performance testing. The hardware requirements for the prototype system were implemented with an off the shelf microprocessor and visual display. The development and testing of the software to demonstrate the image shift method was completed for a scotoma simulator integrated into an image shifting algorithm. Preliminary testing of the system on human subjects was combined with parameters from published reports to specify the spatial and temporal limits for linking and shifting visual images based on eye movements.

Subjects

Two of the subjects were drawn from a graduate and undergraduate population, aged 20-24, and two subjects were aged 42-46; all had normal correctable vision. They

were familiar with eye movement measurement but not with the effects of the image shift method. All subjects served in one or two sessions from 1 hour to two hours in length.

Procedures

The subjects were instructed to position their right going saccade to the blank screen area approximately 1.5 scotoma radius units away from the true target position. It should be noted that our initial tests with three subjects and two targets created confusion in the subjects as to which target was shifted. Therefore, in these data the image shift paradigm consisted of one target, instructions to look back and forth from the target image to a blank screen area to the right of the target, and an image shift area to the left of the target. This shift area corresponds to the preferred area for eccentric viewing, chosen spontaneously by most subjects in a series of previous studies by the author and others.

The left side shift position was maintained consistently while subjects were given a series of trials with three scotoma sizes and three levels of delay. The subjects were given only basic instructions on the image shift method in order to observe any stereotypes associated with the image shifting effect on eye control. Three levels of scotoma size and three levels of target fixation to image shift delay were selected with pilot tests. The resulting nine conditions were given with 2-6 repetitions per condition, in the order from largest to smallest scotoma and shortest to longest delay. The subjects were fully informed of the scotoma size and delay interval before each condition.

The basic visual task required recognition and maintenance of a clear monocular view of a target location window into which were presented an overlapping stream of numerals (0-9), similar to Rapid Serial Visual Presentation, at the rate of two per second, each overwriting the next within a single location over a maximum 90 second trial. The subject monitored the target stream for the occurrence of the number "8", randomized for position and occurrence in the stream for each trial, and he pushed a button to this intermittently occurring target. During all tasks rest breaks were given every 5 minutes or as needed.

Variables and analysis

The preliminary tests established that the independent variable of inter target distance must be set according to the scotoma size. A scotoma size of 120 minarc radius meant that the minimum distance between left and right side fixations could be no less than 130 minarc (120 minarc scotoma + 10 minarc target size)—if the targets were closer, a fixation to one would obscure the other with the edge of the computed scotoma boundary. After pilot tests, the second target position was eliminated from the experimental design because it became clear that the subjects could reliably produce saccades with only one target and the proper instructions. One target also made the saccade production task simpler for the subjects to learn quickly. Two shift targets were considered as an approximation to a working system but since these were preliminary tests additional shift targets were left out in order to maintain simplicity and reasonable workload for the available hardware, software and subject instructions.

The scotoma sizes were selected to approximate a wide range of deficits that might be expected in an operational context. The largest scotoma, 120 minarc radius, covered an area large enough to simulate the loss of foveal and parafoveal retina from a flash aftereffect or a clinically significant case of functional loss due to macular degeneration. The small scotoma, 30 minarc radius, was sized to produce deficits with the numerical imagery selected as recognition targets. This was larger than the smallest scotomas known to

produce deficits in visual search (Bertera, 1989) but they were included to evaluate the effect of scotomas on abnormal oculomotor responses.

The three delay intervals were selected to cover the widest range that could be utilized in any image shifting system, for either controlling reflex foveations or due to hardware/software processing delays. The zero delay condition was designed to provoke the strongest tendency to refixate the shifted target, i.e., to track the target image. The 0.5 second and 1.0 second delays were set at a nominal 497 msec and 994 msec for convenience in synchronizing the sampling rate with image shifting.

The x-y eye position samples along with the associated durations were stored on computer disk. The samples were analyzed for the presence of fixations (typical criterion: dwell >100 ms within 10 minarc area), dispersion of fixations around the targets, eye fixation duration, saccade length and spatial distribution. Error fixations in this paradigm consisted of fixations which did not land the scotoma exactly on the target and therefore this definition is different from error fixations in other eccentric viewing paradigms. Drift movements were dropped from the analysis because in this study it was found that drift movements seen in most earlier studies of eccentric viewing were virtually eliminated and except for normal post-saccadic drift there were few drift episodes to analyze. Data were also eliminated from the analysis if there were any large head movements, track losses or blinks.

Scotoma and image shift algorithms

The scotoma boundaries were calculated after each eye position sample and any displayed imagery within the scotoma boundary was masked or erased. Only invisible scotoma edges were used so that the target simply disappeared when the scotoma boundary passed over it. The displays used in these studies employed rasters with a white background and black foreground, the normal relation for text on paper. The display resolution was 1.7 min per pixel horizontal and vertical. The contrast was approximately 95%. The approximate luminance of the background was 1.9- 3.0 cd/m² and the foreground was .7-1.0 cd/m² depending on screen position.

The scotoma delay (SD), different from the image shift delay, is the time taken to cover, obscure, or degrade the scotoma area of the display after the eye has moved to it. A long delay between eye movement and the updating of the scotoma position makes the display imagery easily visible, depending on the contrast between the scotoma and display image. Delays less than 16 or 32 msec between eye movement and scotoma movement are not found in commercially available video raster displays. A zero delay, the ideal, is only possible in a case of true retinal lesion or with an afterimage from strong light sources. The SDs evaluated in the simulators in this project ranged from 5-16 msec.

Apparatus

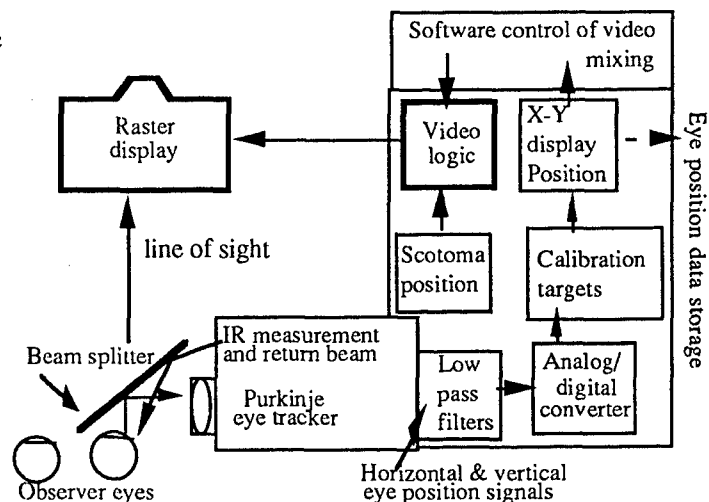
A major problem in an eye controlled simulator is accurately detecting and converting eye position coordinates into degradations of visual information at visual display regions corresponding to retinal scotoma coordinates. Horizontal and vertical analog eye position outputs from a Purkinje tracker (Crane and Steele, 1978) were used to control the scotoma position. The analog outputs representing horizontal and vertical eye position were low pass filtered to limit an overshoot artifact characteristic of Purkinje trackers, digitized at 60 Hz to 200 Hz and stored. Placement of the scotoma was accurate to 5 min of arc or better and accuracy was checked before and after about 80% of trials. The right eye was used to position the scotoma since the tracker only records from the right eye. Some subjects steadied their heads with a dental mould to insure accurate eye movement recordings.

Calibration targets were used to relate eye position voltages from the Purkinje tracker to the display screen coordinates.

The hardware system used for these feasibility tests consisted of an off the shelf microprocessor accelerated to 33 Mega Hertz (MHz), an analog to digital converter for acquiring eye position signals, and an 18 inch diagonal black and white visual display. Central processing units in microprocessors will currently operate at 30-60 (MHz) which is sufficiently fast to transfer 200 pixel square areas around a visual display at >100 Hertz.

A tank sighting system was taken as an example of the concrete implementation of an image shift system hardware requirements. While sighting through an optical system the observer is vulnerable in both eyes to projected radiation, since most sighting system employ binocular optics. In these preliminary tests the subjects wore a left eye patch and viewed the display with right eye only.

Figure 9. The Image Shift and scotoma simulator are diagrammed with Purkinje Tracker, computer control elements and raster display for use in Phase I. Right eye positions are measured and the X-Y analog outputs are converted to gaze position relative to visual display using individualized calibration values. Scotoma movements obscure display imagery corresponding to a disk centered on fovea, & are accurate to within 5 minarc. Targets are copied & shifted out of the the scotoma display region at each change of eye fixation position. The scotoma and visual display are integrated together within the same raster monitor.



Software implementation

The software design consisted of three main modules: 1) eye position calibration, recording, and analysis 2) image copy, erase, and shift to peripheral location, 3) visual target presentation with recording of recognitions by the subjects push button. The three functional modules were divided across a real time program that ran the scotoma simulation and the image shifting algorithm and an off line analysis program for eye movements and manual identification responses which plots the eye position samples so that slow drift, saccades and eye fixations relative to the target positions can be isolated for each target in the display. The eye positions were sampled at approximately 140 Hertz, and the display of the scotoma and shifted image was updated at 82 Hz. These sampling and display rates were more than adequate to reproduce almost all of the eye position signals as well as creating a flicker free image shift to the periphery and a disappearance of the target inside the scotoma without leaving a visible persistence.

For initial testing of the software a manually controlled cursor was programmed to substitute for gaze position so that the cursor could be steered, drifted and jumped around the display to test the effect of the coordination of the simulated scotoma movement and the shifting images. The targets were positioned either in the display center with one target for steady monitoring, or equidistant along a horizontal line. The cursor, like an eye fixation, could then be tested approaching the targets from different directions and speeds to test for perceptual effects of the close coordination of the disappearance of the target within the

scotoma at each "fixation" and the closely coordinated image shift and appearance in the periphery.

Eight increasing delay periods (from 10 msec to 1000 msec) between erasure of the target inside the scotoma boundary and its reappearance at the left peripheral location were examined in pilot tests. It was verified that the size of the target up to two degrees did not add more than 0.5 msec to the shortest delay possible which was 6 msec. The longer delay periods were programmed into a disk resident file, along with other parameters, which was input to the program at the beginning of each trial. The size of the targets, the rate of presentation, the distance between targets in the two target left-right alternation task, the target and scotoma contrast, as well as the X-Y position of the targets on the display and the number of repetitions of trials and the length of the recording period can be altered for each trial.

The analysis program ran off line and gathered a series of files containing eye movement and manual response data, as well as a recording of the various condition codes for each trial. A linear trace of the horizontal and vertical eye position was plotted to examine for drifts, fixations, and saccades, along with a point plot of eye positions overlaid on an icon of the target array for each trial. Summary statistics were extracted from the recorded eye position data relative to each target. Left and right target arrays were analyzed by separating the eye positions samples nearest to each target, forming a set of values for eccentricity from the target, eye fixation duration, the percent time targets were inside or outside of the simulated scotoma and the saccade length.

To test the program for recording and analysis, a set of analog square waves were sent into the eye position inputs and the duty cycle calculated by real time data collection all the way through the analysis and averaging program module. Under increasing loads of copy and shift imagery, variations from true values were less than 5%.

RESULTS of PHASE I

System performance measures

Preliminary tests

Preliminary human test runs were performed to check for design requirements before the contract period began on May 1, 1994. In addition, an eye position sample file collected under corresponding conditions to the target positions and instructions proposed for the Phase I work was run backwards through the real time simulator and image shift program and the resulting scotoma and image shift movements were observed on the visual display for stability.

Next, steadiness of the appearance of the shifted image was evaluated against the effects of normal errors in eye position after a period of steady fixation and with a series of saccades. Of particular interest were small oscillations or noise in the eye position signal which might cause the shifted image to flicker if it was on the border of the scotoma, thus slipping in and out of a scotoma erasure and image shift operation. No oscillations were detected and the image shifting to periphery appeared to be stable under all conditions, even with the fastest system delay intervals (6 msec).

Table 1 shows the average eccentricity from a single target during attempts at steady fixation by four inexperienced subjects. With no scotoma and staring steadily at a 5 minarc target, the average eccentricities ranged from 4.5 minarc to 26.6 minarc, where the ideal fixations would have been zero minarc. The standard deviation rises with the size of the average fixation disparity. From these data it can be concluded that a shifted target should

be positioned a maximum of about 20 minarc from the scotoma boundary in order to allow a steady peripheral view of the shifted image. If the shifted image is positioned closer to the scotoma boundary, the normal small eye movements that occur even during steady eye fixation attempts could produce an intermittency in the shifted image where the target of interest is obscured for a significant percentage of the available viewing time.

The right side of Table 1 shows eye fixation eccentricity comparisons with a 30 minarc radius scotoma. The subjects were instructed to do their best at maintaining an eccentric viewing position and to try to keep the single target visible at all times without making saccades. Perfect adaptation to the scotoma would be an eccentricity of 30 minarc plus the target diameter (approx. 7 minarc). The tabulations under "sector 1" represent eye positions which put the target outside of the scotoma boundary. It is clear that when the target is outside of the scotoma the subject approaches the correct average value, although the standard deviations show that the eye is less stable with the scotoma. The sector 0 eccentricities for the 30 minarc scotoma should be noted since they indicate that the subjects are exerting some inhibition of fixations with the scotoma. If their sector 0 eccentricities were comparable to steady fixation with no scotoma, it would indicate that the subjects were making uncontrolled foveations with the scotoma. A different picture emerges when comparing the percentage of target viewing time (far right column, Table 1) Sector 0 represents eye positions where the target is hidden inside the scotoma boundary. From 11% to about 60% of the available viewing time is taken up while the target is invisible inside the scotoma. This demonstrates that unaided eccentric viewing does achieve good eye positioning but it is inconsistent. The reason for this loss of viewing time are the involuntary drift eye movements and error fixations.

Table 1.

Eccentricity of steady fixations with and without a scotoma—
No image shifting

S#	No scotoma		30 minarc radius scotoma				
	Eccentricity	S.D.	Eccentricity		S.D.	% Time within	
			* Sector 0	Sector 1		* Sector 0	Sector 1
1	4.5	4.2	11.3	76.3	18.3	30.7	69.3
2	13.5	8.3	19.4	35.4	18.9	51.4	48.6
3	10.5	6.0	18.5	36.8	30.5	59.3	40.8
4	**26.6	12.3	18.4	32.4	46.9	11.1	88.9
Mean	13.8	7.7	16.9	45.2	28.6	38.1	61.9

* Sector 0=fixations with scotoma covering target, sector 1=all other eccentric fixations, defined as > scotoma radius plus target size from target location. ** Anomalous fixation score.

A second preliminary task designed to test the image shift system in Phase I was a two target alternation task in which the subjects maintained surveillance on two locations with equal probability of a target occurrence (targets and non-targets were presented at 1-3 per second). The targets were separated by several increasing intervals and the subjects were told to look back and forth frequently to have the best chance of not missing any of the targets. Accuracy was poorer with the largest scotoma on both left and right sides. The 120 minarc scotoma impaired accuracy more than the 30 minarc, also, compared with no scotoma controls (Figure 10 & 11). No-scotoma trials produced good fixation accuracy

with little practice (Table 2). However, after a few practice trials with a scotoma it was clear that the subjects were poorer than with either steady fixation or the no scotoma saccade production condition. The standard deviation was nearly twice the steady fixation value shown in Table 2. If this were taken into account in the design of a range parameter for image shifting it would suggest that the best performance for such pressured monitoring would require placing the shifted image as much as 40 or even 60 minarc from the scotoma boundary in order to create a stable peripheral viewpoint.

Table 2.

Eccentricity (minarc) from target during 40 second trials with no scotoma in a two target saccade alternation task. (Subject Dual 2_1)

Trial number	Left target	Right target
Practice	135	66
Practice	28	37
1	11	9
2	12	11
3	55	37
4	35	34
5	32	22
6	17	27
Mean	27.00	23.33
Standard deviation	17.05	11.60

One conclusion that can be drawn from these figures is that it might be important to experiment with parameters for positioning the shifted image to keep the shift location far enough away from the scotoma boundary to maintain a steady view. Table 2 shows the eccentricities from target locations for the left and right side fixations. Differences in the accuracy in eye positions to left and right side targets (eye movement directions) is an important parameter to explore in selecting a shifted image position.

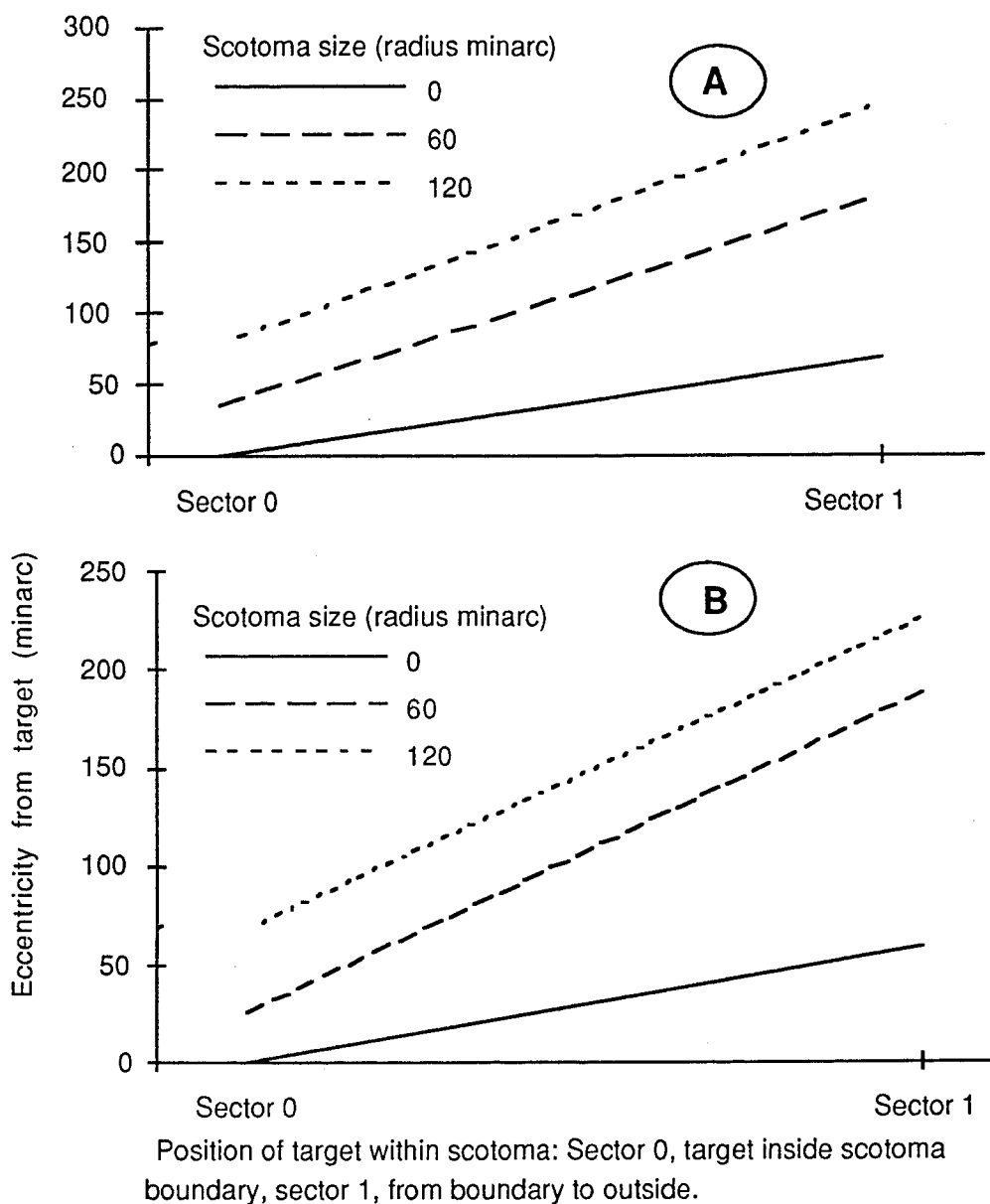


Figure 10. Deviations of eye positions from left side (A) and right side (B) targets during the left-right alternation task, with 0 (no scotoma) & 60 and 120 (minarc radius) scotomas (Subject Dual2_1). Sector 0 includes all eccentricities within scotoma boundary; sector 1 includes all eccentricities outside of scotoma.

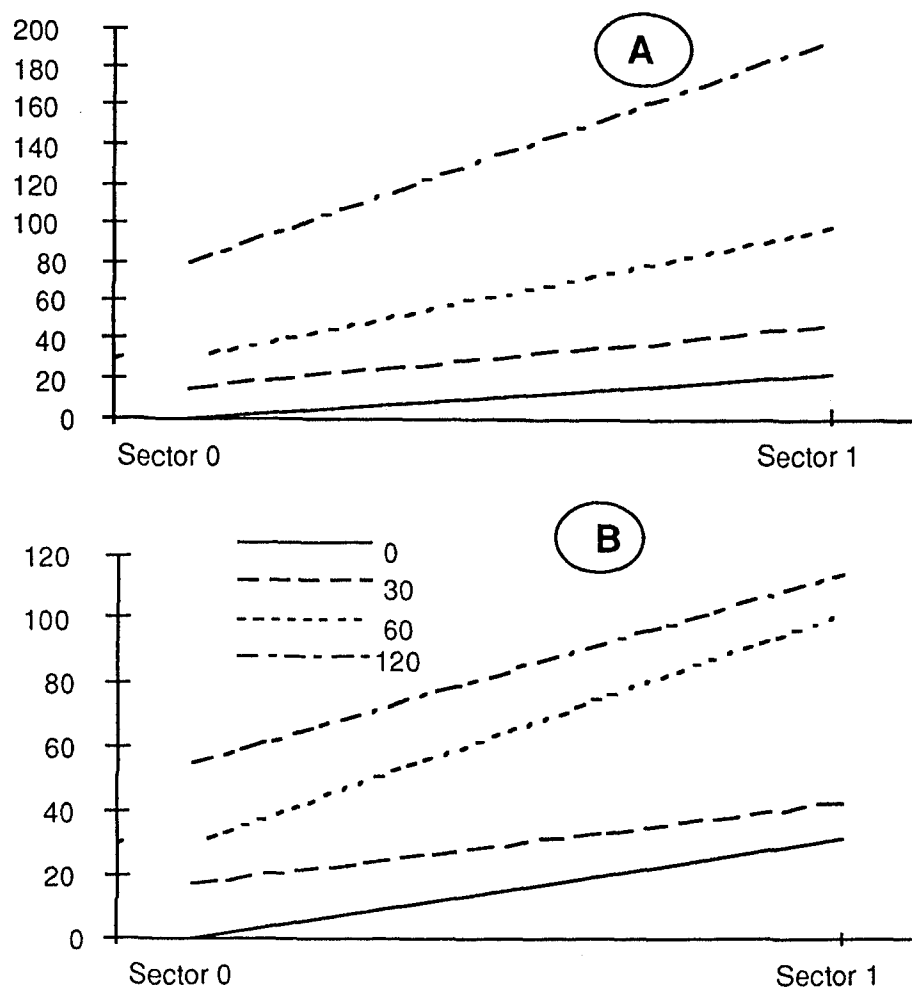


Figure 11. Deviations of eye positions from left side (A) and right side (B) targets during the left-right alternation task, with 0 (no scotoma) and 30, 60 and 120 (minarc radius) scotomas (Subject Dual3_1). Position of target within scotoma: Sector 0, target inside scotoma boundary; sector 1, from boundary outwards.

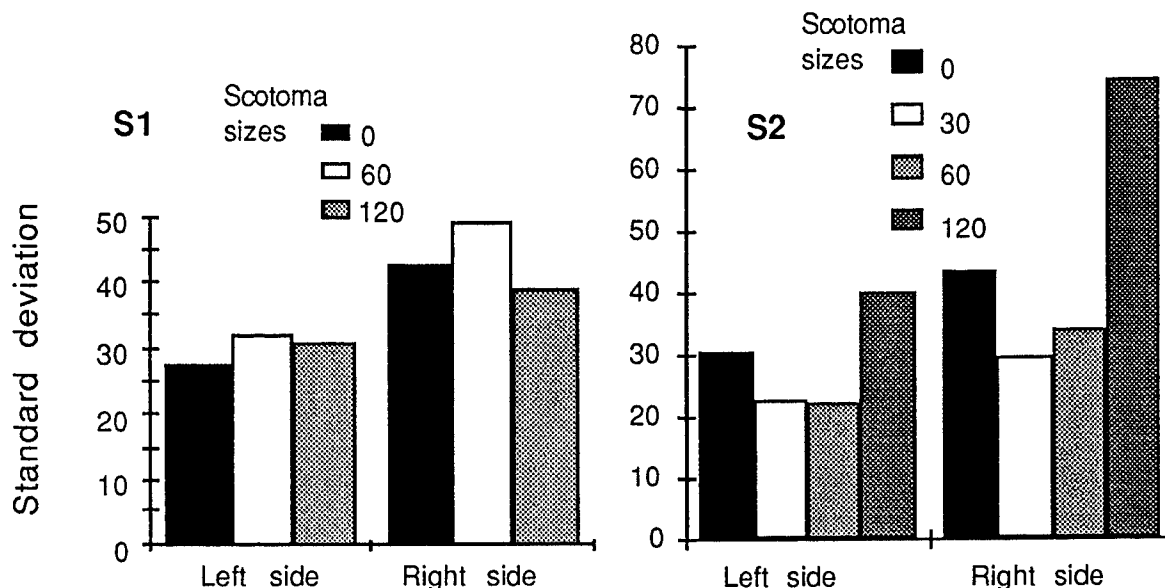


Figure 12. Standard deviations are shown for eye fixation positions to the left and right targets during the two target alternation task for subject 1 and subject 2..

Blinks and track loss in the image shift paradigm

In a simulated scotoma system used for testing the image shift paradigm, losses in tracking of the eye may occur during prolonged blinks and large (>1 degree) head movements. The effect of track losses and blinks were simulated with a test data set and the result observed on the image shift and scotoma visual display. Such track loss events appear to be less frequent than 1 s in two minutes. The scotoma shifts off its stabilized position on fovea and this exposes the target if it is inside the scotoma boundary at the time of the track loss. This effect typically lasted for less than a second, followed by complete recovery of tracking and image shift and scotoma simulation. Faster recovery in a new generation of eye position sensor with higher speed electronics is very likely in the near future so that occasional track losses will not likely be noticeable.

The effect of brief track loss events on image shifting with laser induced scotomas or disease related scotomas, i.e., not simulated scotomas, will be negligible at the present rate of track loss. The effect will be a brief loss of the Shifted Image signal. In the Phase II prototype the shifting algorithm will be set to simply wait before shifting an image if a track loss event occurs, allowing time for the 1 s to recover tracking.

Results of oculomotor variables analysis

The means for individual subjects' oculomotor data are presented in Figures 19-22, and Figure 23 is the second session, subject S1. The mean data across subjects are presented next, at the three scotoma sizes and three delay intervals for fixation duration, eccentricity, saccade length and eye position dispersion on left (target) and right (blank screen) locations.

Fixation duration

Fixation duration changed over most of the trials within subjects but examining the average durations across the subjects there appears to be an increase in duration with scotoma sizes from 280 msec with the 120 minarc radius scotoma, to 303 at 60 and 328 at 30 minarc radius scotomas and the linear effect is significant ($p < .05$) as shown in Table 3. These changes can be attributed to the adaptive process as subjects adjust to the loss of central vision during the scotoma simulation. We pursue this effect in another analysis of the order 3 cubic effects which are marginally significant and the effect is due to linear increases in duration in the 120 and 30 minarc scotomas but not the 60 minarc condition (See Figure 13).

Eye Fixation Duration

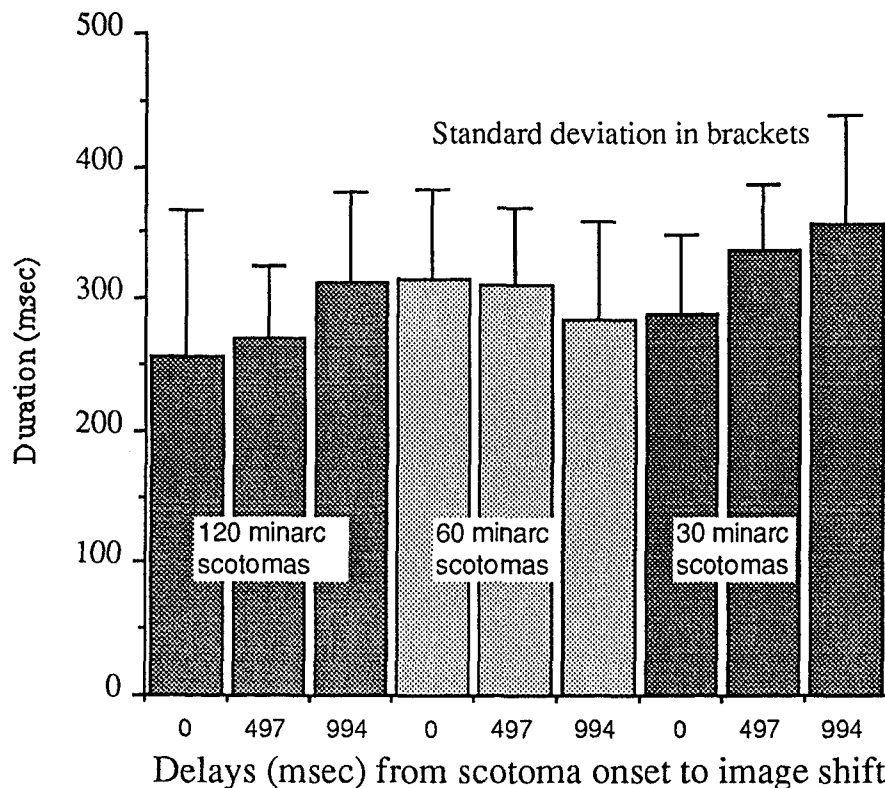


Figure 13. Eye fixation duration across scotoma and delay conditions showed a marginal cubic effect ($p < .05$) in post hoc analysis. Both the 120 minarc radius scotomas and the 30 minarc radius scotoma conditions increased duration with longer delays, suggesting that subjects adapted their fixation duration to delays in these conditions. However, with 4 subjects in the analysis this cubic effect was not significant.

Table 3.

Analysis of variance components for eye fixation duration
across scotoma and delay conditions (n=4, see Fig 13 & 14.)

POLYNOMIAL TEST OF ORDER 1 (LINEAR) N=4

SOURCE	SS	DF	MS	F	P
Scotoma	32782.042	1	32782.042	11.320	0.044
ERROR	8687.708	3	2895.903		
Delay	24929.260	1	24929.260	4.749	0.117
ERROR	15747.115	3	5249.038		
Scotoma					
*Delay	676.000	1	676.000	0.131	0.742
ERROR	15510.875	3	5170.292		

POLYNOMIAL TEST OF ORDER 3 (CUBIC) N=5

Scotoma					
*Delay	10666.667	1	10666.667	8.551	0.043
ERROR	4989.542	4	1247.385		

Fixation accuracy

Fixation accuracy on the fixed target was good during image shifting and remained stable over practice which fits well with an application using these "blind" saccades to guide an image shifting system.

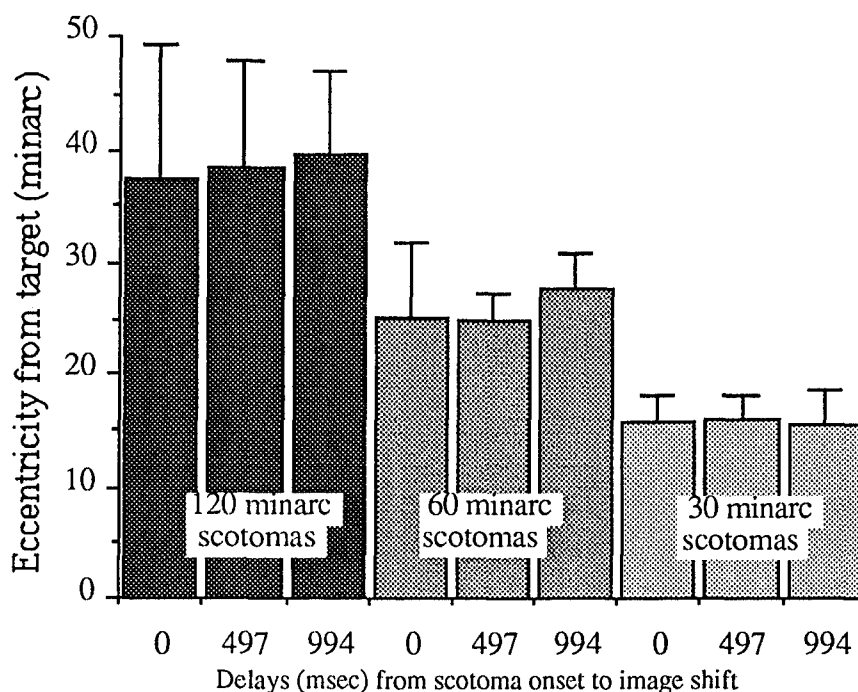


Figure 14. Average eccentricity from target at the end of each left going saccade. The largest scotoma produced the greatest deviation at all three delays, progressively less for the 60 and 30 minarc scotomas. Standard deviation in brackets. No appreciable effect of delays up to 1 second from scotoma onset to image shift.

Table 4
Analysis of variance of average eccentricity from target,
across scotoma and delay cells

POLYNOMIAL TEST OF ORDER 1 (LINEAR)

SOURCE	SS	DF	MS	F	P
Scotoma	3601.500	1	3601.500	21.780	0.019
ERROR	496.083	3	165.361		
Delay	11.344	1	11.344	0.408	0.568
ERROR	83.448	3	27.816		
Scotoma*Delay	5.060	1	5.063	1.568	0.299
ERROR	9.688	3	3.229		

Subjects are well able to maintain a good fixation landing to a fixed target even when their starting position varies from saccade to saccade. Typical of saccades over two degrees, the fixation landings generally undershot the correct position rather than over shoot. The mean eccentricities vary significantly across scotoma sizes ($p < .05$), in Table 4.

The accuracy of eye control measured by eccentricity for the subjects in Figure 14 compare well with fixation accuracy in the single target monitoring task without repetitive saccades. The eccentricity values with no scotoma and a 30 minarc scotoma (shown above, Table 1) without image shifting, are approximately 14 minarc and 16 minarc, respectively. The similarity of the 14 minarc error and the 16 minarc eccentricity errors suggest that the fixations made deliberately in the repetitive saccade method of image shifting and the reflexive uninstructed fixations are controlled by the same process.

Saccade length

The average saccade lengths ranged from 142 to 121 minarc in the three scotoma size conditions and no effect of delay was apparent within conditions. These saccades correspond to the radius of the largest scotoma and it makes sense that the naive subjects would use this size saccade since it was the largest size demonstrated in the preliminary trials to acquaint the subjects with the procedures. Optimum adaptation would have been saccades of 130, 70 and 40 minarc in the three scotoma size conditions. It seems likely that near optimum saccade sizes could easily be achieved with additional training based on the rapid learning in this first session. Higher variability in the second half of the session (Figure 15), while the saccade length began to decline, suggests that the subjects began exploring the effect of shorter saccades.

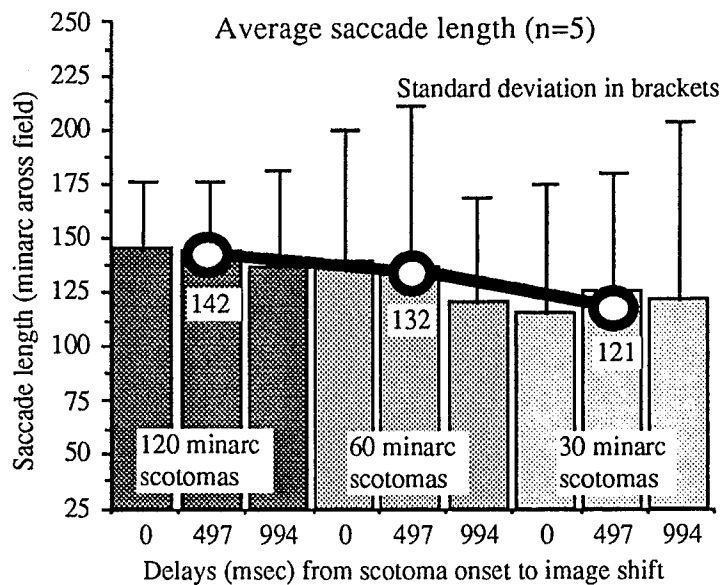


Figure 15 Average saccade length across scotoma and delay conditions shows shallow downward trend, NS. The subjects maintained a minimum saccade length approximately equal to the largest scotoma size.

Dispersion of eye fixations

The dispersion of eye positions at the left (around the target position) and the right (blank screen area) were calculated over each condition as the measure of consistency in positioning (Figure 16). Although the right side dispersions are greater than the left, they are still stable considering the range of screen positions the subjects could have taken. Some subjects were very consistent in their blind fixations on the target location (the fixations that triggered the image shift), as well as the right side fixations (See last frame of Figures 19, 20, 21 & 22). It is useful to recall that the subjects were told that they could position their right going eye movements wherever they chose on the screen, i.e., no instructions were given for accuracy or consistency in right side, blank screen, fixations. But, explicit instructions to fixate the left side target location, even though it disappeared on fixation, are likely the cause of the tighter dispersion of eye fixation positions on the left.

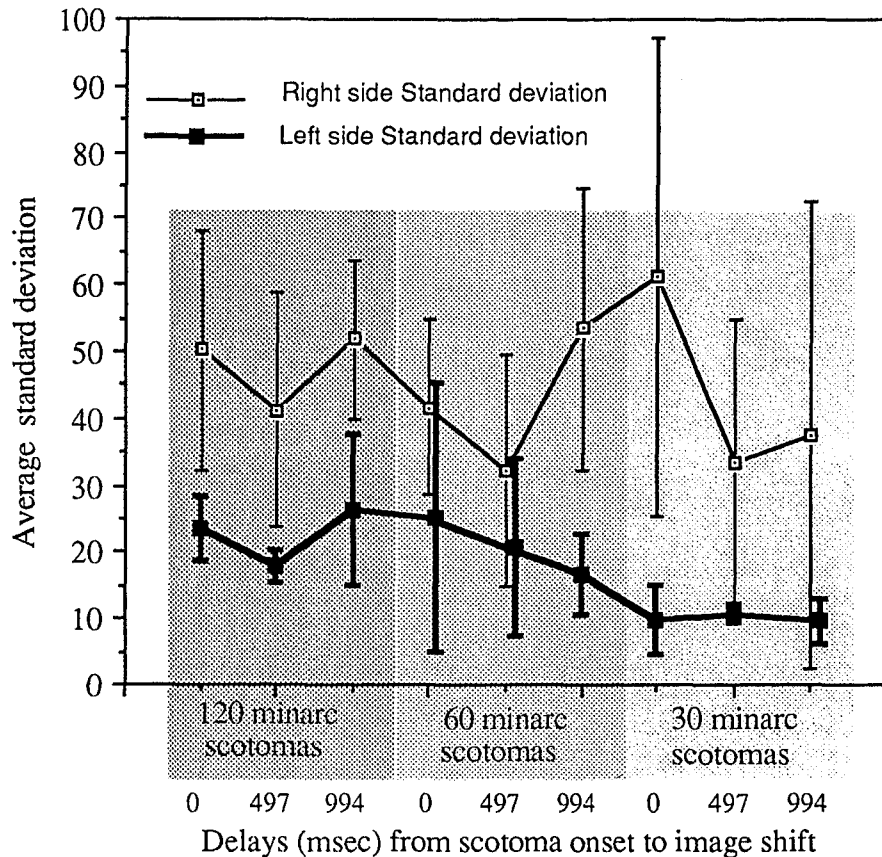


Figure 16. Combined dispersion scores (standard deviation) for the left side and right side eye fixations. Subjects clustered their fixations more consistently on the instructed target, even though their right side fixation position varied. Subjects maintained good accuracy on the left side target location with different size saccades, a required characteristic for an operational image shift system. S4 was dropped from these calculations because the left was much more dispersed than right.

Error eye movements: fixations to the shifted target and drift movements

There was very little tendency to make error fixations by tracking the shifted target with saccades. Even though these subjects had only one session of practice, they exhibit good inhibitory control of the reflex to foveate the target image after it was shifted to the left periphery (See Figure 17). There were many missing cells where no error fixations were made, therefore, the many zero cells were dropped from the average calculation. Therefore, while the 10-11% error fixations seems small for this early training session it is still an overestimate. Inhibitory eye control for this type of reflex foveation to the left shifted target was very good—an important factor for an image shifting system.

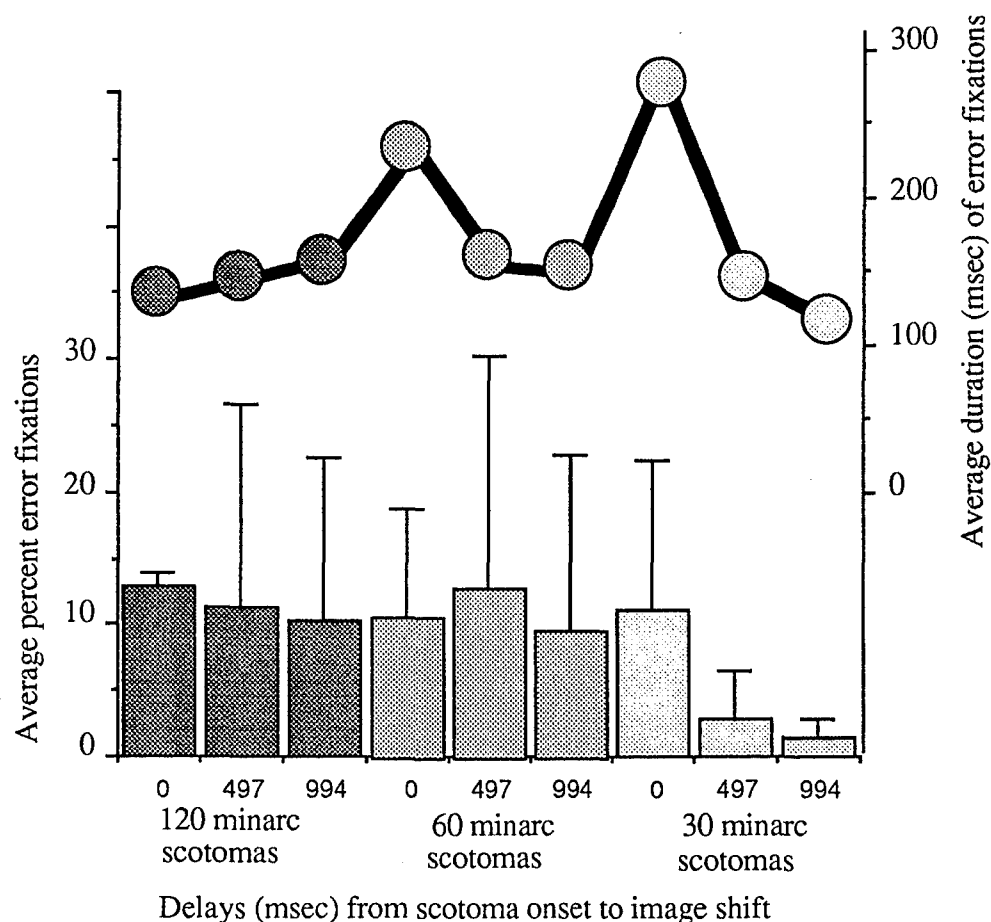


Figure 17. Error fixations (bottom panel) to the shifted image averaged across subjects. Subjects with zero errors are excluded. % errors ranged from 12%-1%, a low rate for little practice, indicating good inhibitory control during image shifting. Fixation durations (upper panel) were shorter than average for the correct fixations (cf. Figure 13).

The second error eye movement type, long lasting drift (> 500 msec epochs), was absent even though these drift movements were prevalent in other studies of eccentric viewing of a single fixed target. The systematic production of saccades appears to have eliminated the slow drift movements which are hypothesized to be the source of hyper-eccentric fixations after saccade returns from drift. Normal post-saccadic drift did appear in some subjects, sometimes on the left or the right side fixations. But, these small drift episodes were less than 0.5 s long and did not alter the fixation landing position significantly relative to the shifted target.

The 30 minarc radius scotoma was small compared to the size of debilitating clinical scotomas of 5 degrees and larger. The present data showed that this size of scotoma was small enough to produce inconsistent shifted images for most subjects since their normal error range in fixation landing sometimes left the target outside of the scotoma boundary so that the target remained visible after the left going saccade. This should be kept in mind when reviewing data from the 30 minarc scotoma conditions which are included here for completeness even though they produced fewer shifted images. This effect of fixation dispersion might be expected under more realistic small scotoma conditions.

Results of performance analysis

The percentage of correct target recognitions were calculated for each condition and subject and where recognition was zero the cell was treated as missing data. All subjects had cells with some zero recognition, especially early in the session. Figure 18 shows the cumulated percentage of mean recognitions. The missing data precluded a variance analysis but there appears to be an improving trend in performance during the session. The individual subject performance scores are shown in the next section, Figure 24. The first subject was given a preliminary practice session during tests of the calibration and trial control software module which probably accounts for the 50-75% recognition in most conditions.

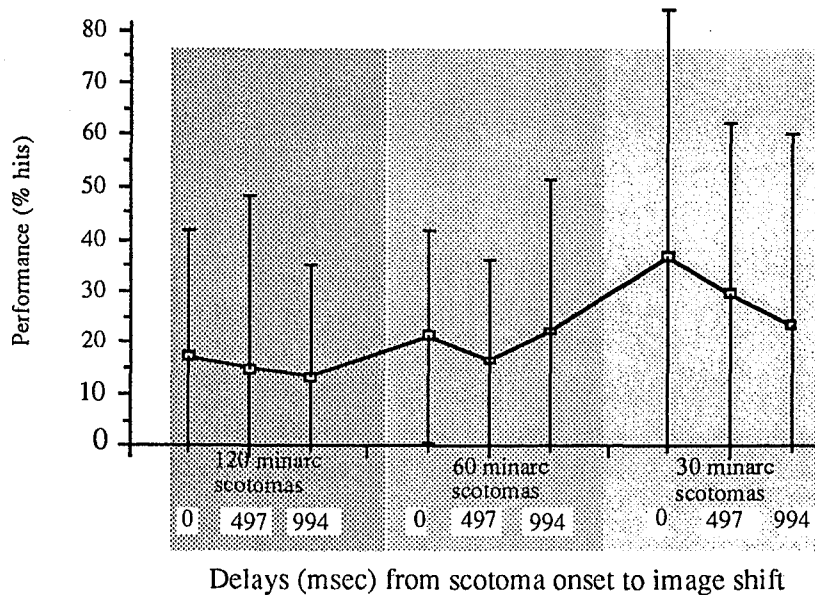


Figure 18. Recognition performance averaged across subjects and across cells with missing data. All subjects had some cells with missing data (i.e., 0% hits), especially earlier in the session. Expected improvement in performance due to a smaller scotoma was not significant. 20-35% improvement from zero in these subjects suggests that the image shift method as implemented is useable with little practice in image shifting.

The comparison condition is where the subject makes no recognitions because the target is within the scotoma boundary for at least half the available viewing time and is in a hyper eccentric position for much of the remaining time, as shown in earlier data from Figure 8.

Individual subject oculometrics and performance

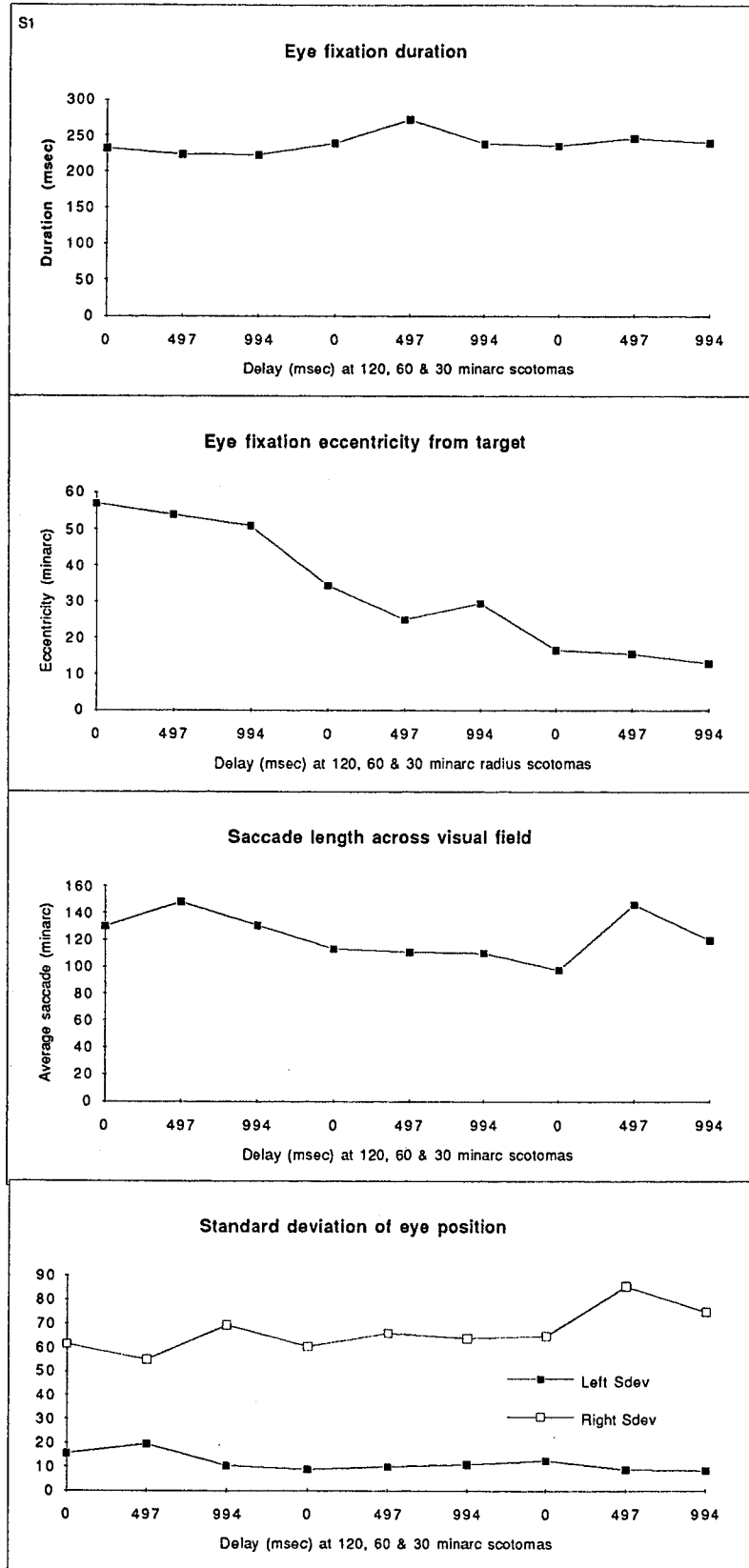


Figure 19. S1. Eye fixation duration remained stable around 250 msec across the scotoma and delay conditions. Eye fixation eccentricity fell with each scotoma size from 55 minarc for the 120 minarc scotoma to 18 minarc for the 30 minarc scotoma. Saccade length varied between 110 and 150 minarc across conditions indicating the subject used the same saccade length even for smaller scotomas. The standard deviation is smaller for the left side eye positions (saccades to the target position) and four times larger for the right side fixations made to the blank screen area where the subject had no visible target for saccades.

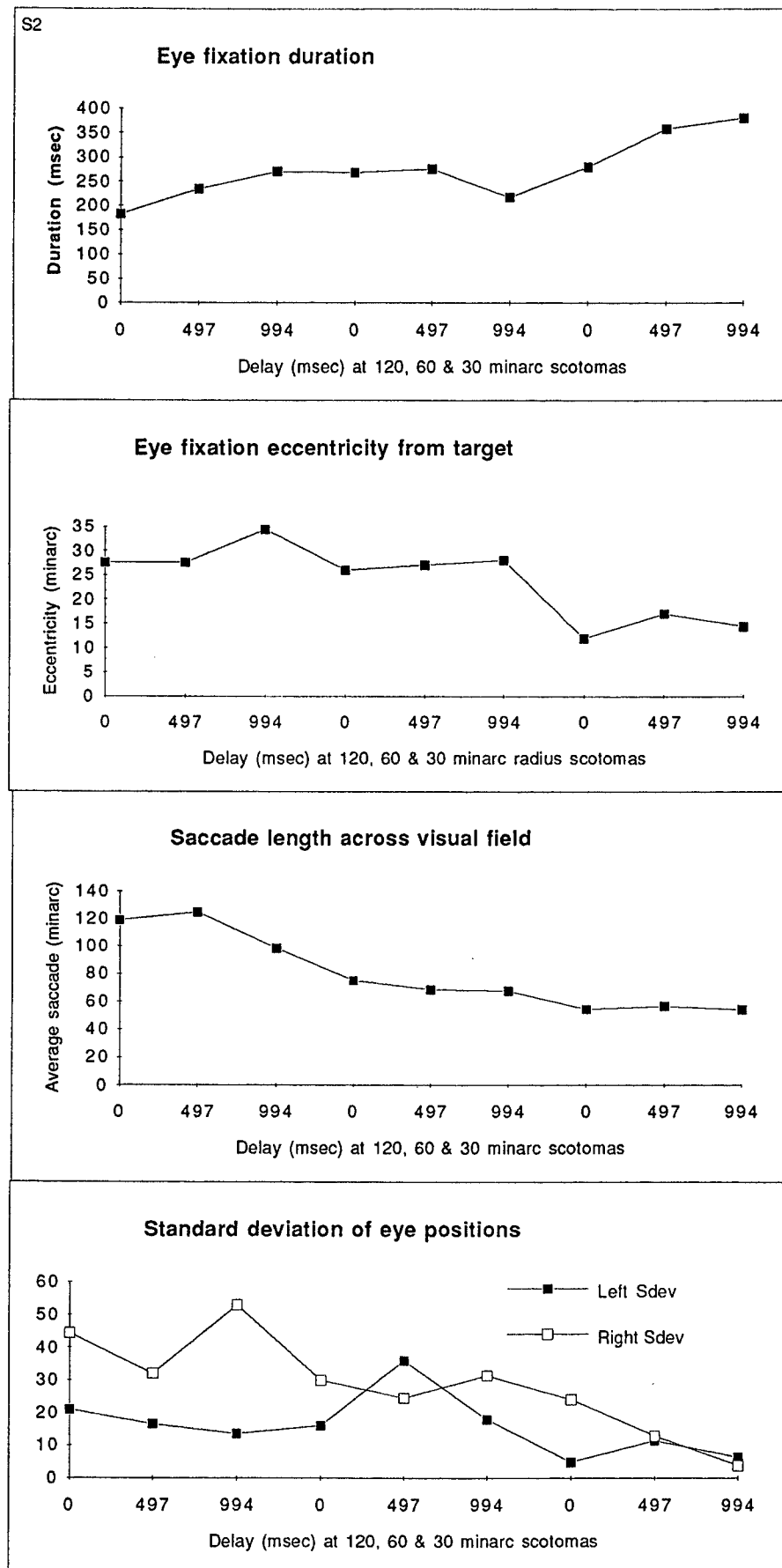


Figure 20. S2. Eye fixation duration is less consistent than S1 but remains in the range of 200-350 msec over most trials with no systematic adaptation to either scotoma size or delay. Eye fixation eccentricity is adaptable from a high of 33 minarc for the 120 minarc scotoma to approximately 15 minarc for the 30 minarc scotoma. Saccade length declined across the scotoma conditions from 125 minarc to 59 minarc. The standard deviation is smaller for the left side fixation positions indicating good accuracy to the target location but more dispersion for the right side fixations where there was no target.

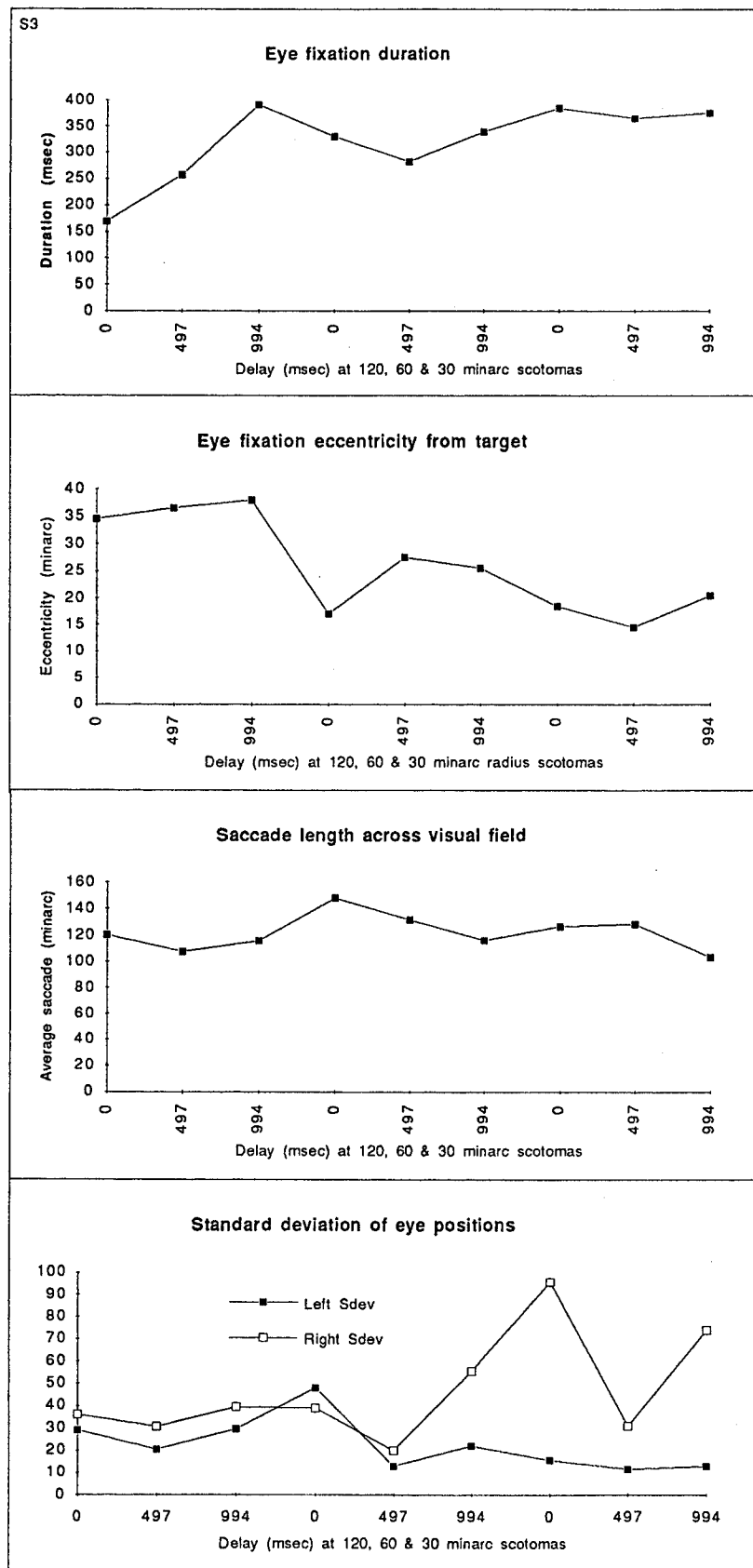


Figure 21. S3 Eye fixation durations extended across a larger range (160-400 msec) with a shallow upward trend with smaller scotoma sizes. Eccentricity declined from 35 minarc to 16 minarc across the scotoma conditions. Average saccade length remained in the range of 118 to 150 minarc. The standard deviation was marginally smaller for the first half of testing on the left side compared to the right side fixations with no target, but the right side fixations generally increased in variability for the two smaller scotomas.

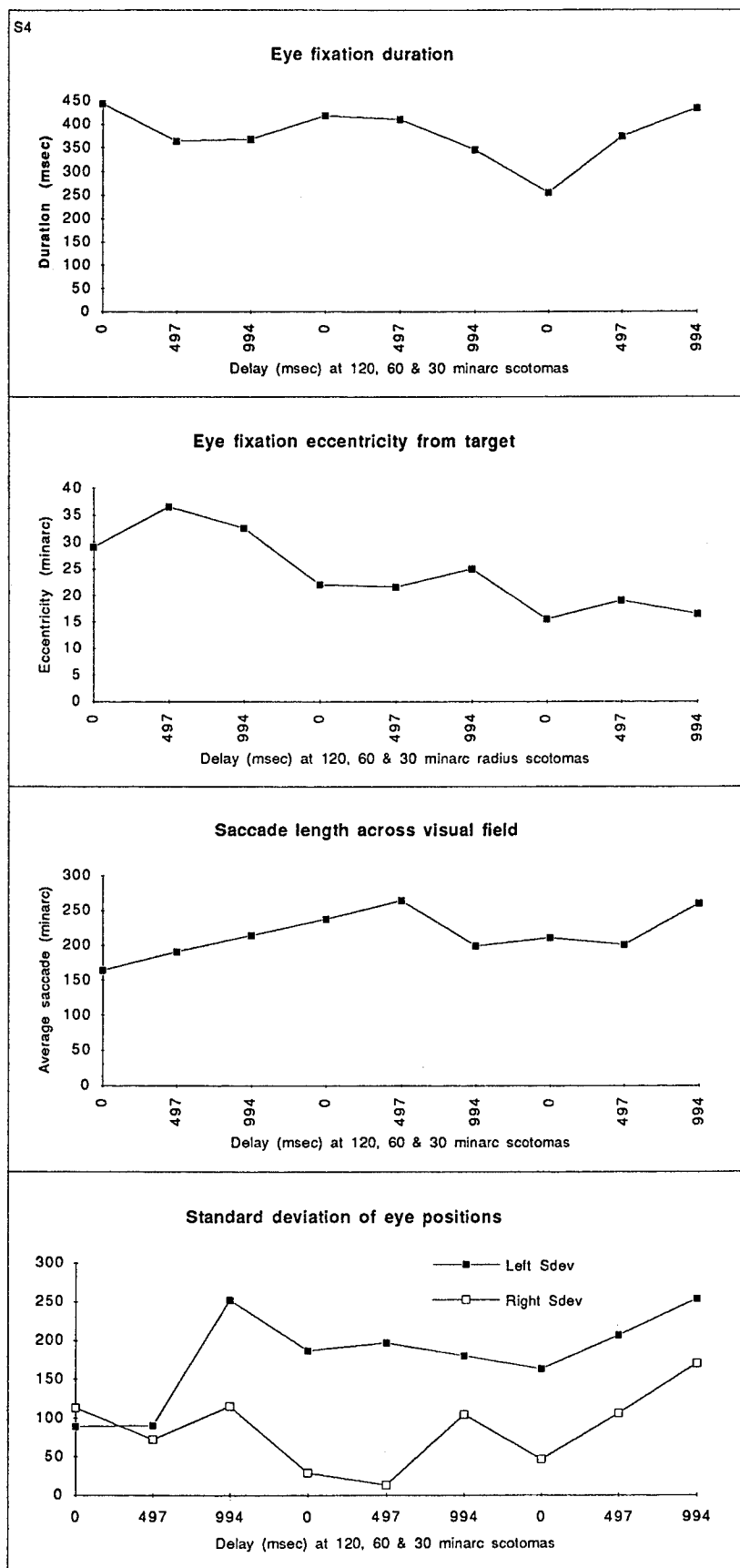


Figure 22. S4 Fixation duration showed the largest range, from 450 to 280 msec across conditions. The fixation eccentricity was again systematically declining across the three scotoma size conditions with little change at the delay intervals. The saccade length shows a linear increasing trend from 160 to 260 minarc, but then declines slightly. The standard deviation was larger for the left side fixations, opposite to the other subjects, and larger overall.

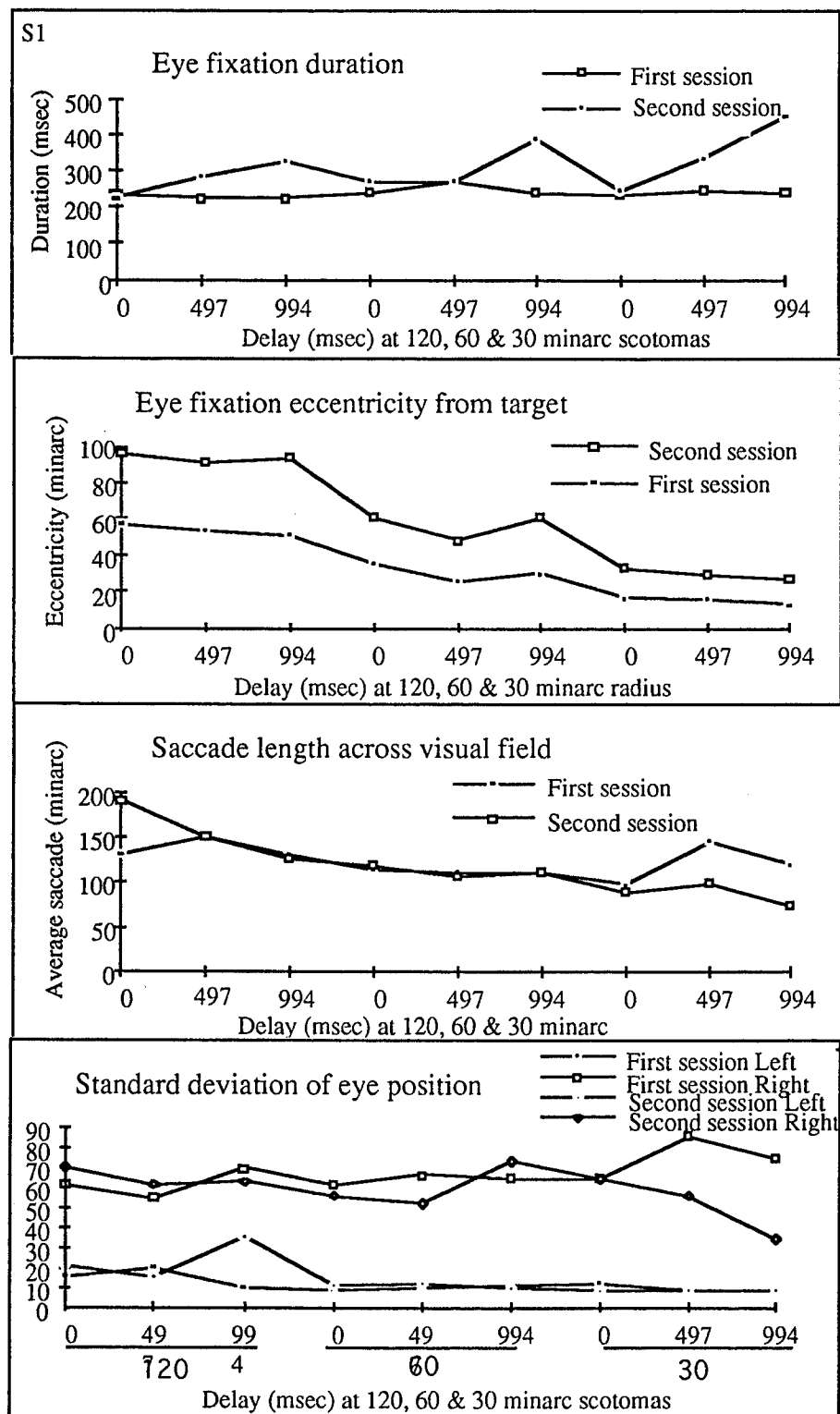


Figure 23. First and second session eye movement averages for S1. In the ongoing test program S1 was tested in a second session and consistency in eye control is apparent across all four variables. Fixation durations remain within 100 msec across conditions except for the 1 second delay at the 30 minarc scotoma. Eccentricity averages track conditions very well, with a slight increase apparent at the 1 second delay in the 60 minarc scotoma condition for both sessions; the second session showing greater eccentricity in all conditions. The saccade lengths are almost identical throughout with divergence at the start and ending, with similar patterns for the standard deviations.

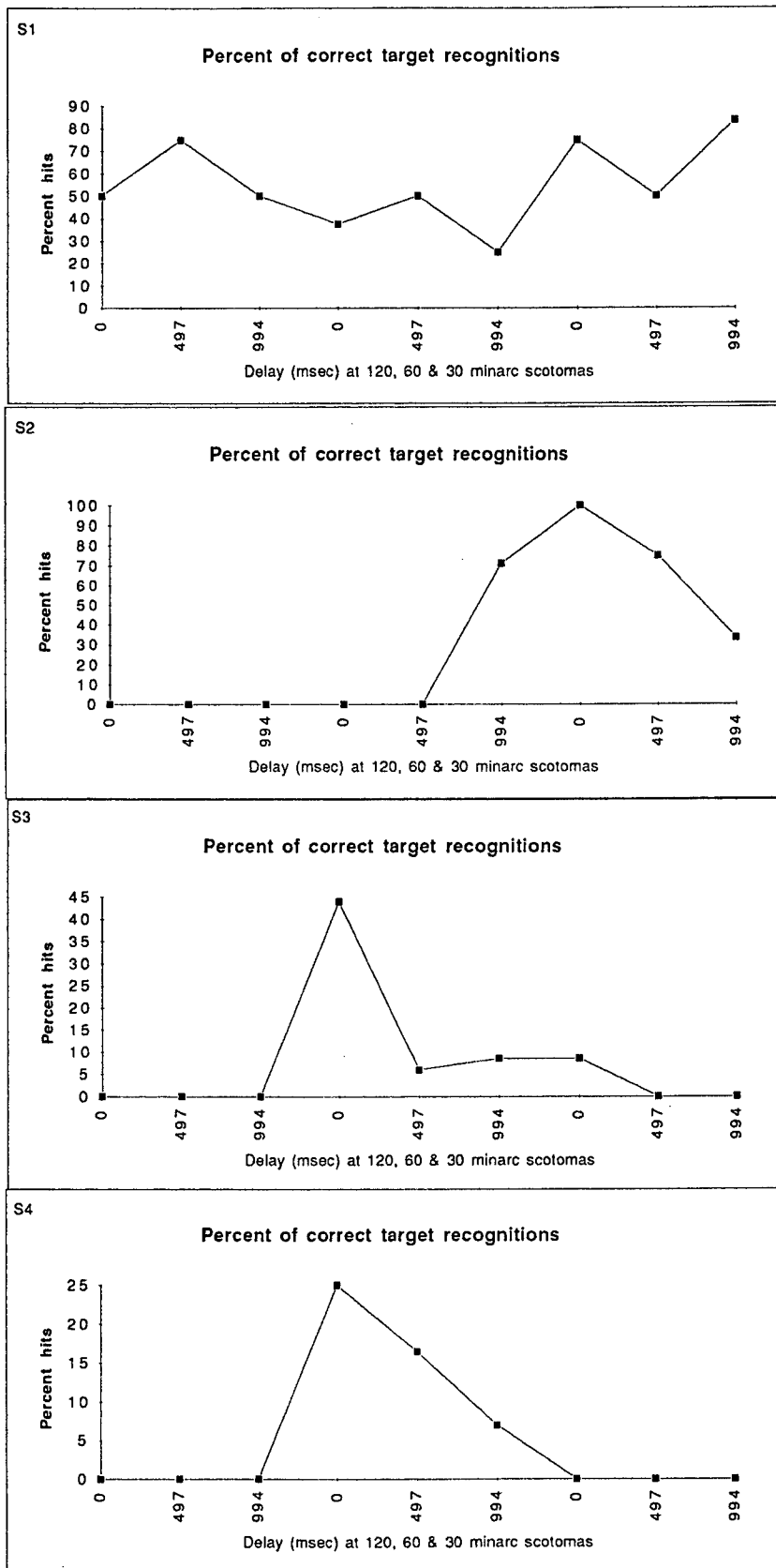


Figure 24. Percent correct recognitions were variable in this group of untrained subjects, except S1 who was given preliminary practice; but all naive subjects showed improved performance in the second half of their session. The poorer performance in the 30 minarc conditions is probably due to a combination of hyper-eccentric fixations to the right and the smaller target image in the 30 minarc condition.

CONCLUSIONS and IMPLICATIONS

Hardware and software components are achievable within a two year development program with presently available technology to implement image shifting procedures, within a size weight and cost to be feasible for application within sighting systems. A disjointed design could allow a hand held or helmet mounted component along with a remotely placed processor.

Blind guidance appears to be a feasible method for use as the targeting element in an image shift system to aid the recovery from central visual loss. Subjects were easily able to make sufficiently accurate saccades to a target location even when the target disappeared on on fixation there. This accuracy was maintained even though the starting point for their "blind" fixation on the target position was begun from a different starting point for each saccade.

The error movements of incorrect tracking of the shifted target and eye drift were minimized, under control of the saccade production paradigm. How few saccades are necessary to eliminate error eye movements is one question worth following.

The largest scotomas that could be expected from exposure to laser radiation, four degrees in diameter, produced oculomotor behavior within reasonable limits to maintain operation of an image shifting system.

Delays from target fixation with the scotoma to image shift to the periphery were no problem in distorting oculomotor behavior. The longest delays of 1000 msec produced no system changes in eye fixation duration, eccentricity from target or saccade length.

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